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COACCH

CO-designing the Assessment of Climate CHange costs

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D4.2 Sectoral assessments of policy effectiveness

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Contributors:	Onno Kuik (VU), Wouter Botzen (VU), Max Tesselaar (VU), Predrag Ignjacevic (VU), Birgit Bednar-Friedl (Uni Graz), Nina Knittel (Uni Graz), Eva Preinfalk (Uni Graz), Stefan Borsky (Uni Graz), Joachim Raich (Uni Graz), Jaroslav Mysiak (CMCC), Dionisio Perez Blanco (CMCC), Arthur Essenfelder (CMCC), John Tarpey (ECOLOGIC), Jenny Troeltsch (ECOLOGIC), Hannah Hennighausen (Uni Graz), Kees van Ginkel (Deltares), Ad Jeuken (Deltares), Benjamin Leon Bodirsky (PIK), Miodrag Stevanovic (PIK), Paul Watkiss (PWA), Alistair Hunt (PWA), Daniel Lincke (GCF), Jochen Hinkel (GCF)

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CO	Confidential, only for members of the consortium (including the Commission Services)	
CI	Classified, as referred to in Commission Decision 2001/844/EC	

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Version log

Version	Date	Released by	Nature of Change
1	06/April/2021	Onno Kuik (VU)	Zero draft
2	23/June/2021	Onno Kuik (VU)	contributions PIK (2.1), UNIGRAZ (2.2, 3.2), IIASA (2.3,3.3)
3	24/June/2021	Wouter Botzen VU	Edited 2.3 and executive summary
4	27/June/2021	Wouter Botzen VU	Added health section by PWA
5	30/July/2021	Onno Kuik VU	Final Editing
6	07/03/2022	CMCC	Last revision incorporating reviewer comments

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• Deliverable summary

This deliverable (D4.2) substantiates that part of the activity of COACCH Task 4.2 consisting of assessing policy effectiveness for European policy makers and includes a set of case studies examining policy effectiveness from sectoral and thematic perspectives. More specifically, this report elaborates on the following main findings:

Policy effectiveness in agriculture. With the Farm-to-Fork strategy, the European Commission gave itself a vision for a fair, healthy and environmentally friendly food system (EC 2021). In particular, the food system shall be aligned with the EUs ambitious targets to limit global warming to 1.5°, avoiding the most severe climate impacts. Yet, it still remains little analysed by which policy approaches these strategic aims shall be accomplished.
In our policy effectiveness assessment in agricultural business, we compare different policy approaches that are in line with these climate targets but that follow different policy paradigms. We distinguish six different paradigms: A market-oriented paradigm (S2), a behavioural paradigm (S3), a technology-oriented paradigm (S4), a policy-steered paradigm (S5), a mixed paradigm (S1) and the current paradigm (S6). Each of them combines a package of policy measures and a different degree of integration over different economic sectors, and results in different outcomes for producers, consumers and the environment. Within these scenarios, agricultural production changed most strongly in the behavioural and mixed paradigm with a high reduction in animal products and a reduction of import dependence from oilcakes. In the mixed scenario, moreover, the highest increase in bioenergy cultivation was observed. In terms of consumption, the behavioural change scenario assumed changing diets and reduced food waste and therefore also resulted in lower food expenditures; but in general food expenditures for primary agricultural commodities remained very low in Europe in all scenarios. The contribution of agriculture to the 1.5° goal was highest in the behavioural change scenario, and lowest in the market and steered paradigm. However the market scenario also provided high quantities of bioenergy which contributed to emission mitigation in the energy sector. The behavioural change scenario was also effective in reducing nitrogen pollution; land use change (national and international) did not differ substantially between the policy scenarios. Different policy paradigms in Europe also had a limited effect on international emission leakage for greenhouse gases; the reason may be that in our scenarios all other world regions also had some mitigation policies in place.

Policy effectiveness in industry and business. While many industrial sectors are highly aware of risks posed by climate policy such as the EU ETS, the topic of climate change impacts on industry is a relatively new one. The manufacturing industry, as

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the backbone of most industrialized economies, increasingly recognizes the physical risks implied by climate change as a second area of action next to mitigation. In the first part of this case study, we evaluate to which physical climate risks the manufacturing industry adapts, which adaptation actions are taken, and which adaptation drivers and barriers prevail. We find that storm, heat, drought and flood are mentioned most often as climatic risks, translating most frequently into impacts on production processes, but also affecting management, supply chain and procurement, and sales markets. Soft adaptation measures, and in particular risk management and planning, are mentioned more frequently than hard measures, with infrastructure design and adjustment dominating in the latter category. Ecosystem-based adaptation plays only a minor role. Many companies appear to underestimate physical risks and therefore adapt insufficiently; the implementation of adaptation measures can be increased by governments by supporting knowledge exchange, providing technical assistance, financial and other incentives.

The second part of the case study looks more closely into supply chain risks due to extreme weather events. We find that supply chain shocks from upstream input suppliers significantly reduce downstream trading partners' export performance. Having a diversified input supplier network dampens the shock as it enables firms to more easily find substitutes for damaged suppliers. A diversified supply chain may come at a trade-off with supply chain efficiency in normal times. Due to their geographical centrality and their role in global production networks, European countries tend to have less concentrated input supply chains compared to countries in Africa, South America and North America. However, European industries strongly differ in the level of supply chain diversification. We find that agriculture, fishing, mining and quarrying and electricity, gas and water are the industries with the least diversified supply chain, and consequently most exposure to shock propagation due to large switching costs.

The third part examines adaptation planning for European supply chains at seaports and their associated supply chain networks, with the North Sea Region as a case study. Six bundles of measures were established: those targeting port infrastructure, the hinterland transport infrastructure, green or nature-based solutions, supply chain management measures, logistics/supply chain digitalization, and "soft" and risk management measures. Subsequently, these bundles were arranged into a set of adaptation pathways, with different measures implemented in the short (2020-2050), medium (2050-2080), and long term (2080 and later). The highest ranked pathways all incorporate supply chain management measures either in the medium or long term. Digitalisation measures feature in two of the well performing pathways as they are relatively low cost and offer important flexibility. Green measures, as well as risk management measures, are low cost actions that can be implemented in the short term while leaving next steps open for adjustment. European policies such as the EU Adaptation Strategy and the Trans-European Transport Network (TEN-T) will be vital in advancing these adaptation strategies. Adaptation priorities can also be streamlined through funding and investment mechanisms, such as the Connected

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Europe Facility (CEF), the European Regional Development Fund (ERDF), and the Cohesion Fund (CF), and the EU's post-COVID recovery plan.

Policy effectiveness in insurance. Flood risk in the EU is expected to increase with both climate and socioeconomic change. Insurance is an effective mechanism to limit financial vulnerability to this risk of both citizens and governments. The design of insurance systems varies significantly across EU countries, with some systems being better able to cope with issues such as unaffordability of premiums, low insurance uptake, and moral hazard. These issues affect households at risk of flooding, the insurance providers as well as the public sector, who often provides financial aid when insurance coverage is insufficient. This study addresses the policy effectiveness of various flood insurance policies in EU countries and the UK on a macroeconomic scale. For that purpose, we apply riverine flood risk data up to 2050 that was calculated using a state-of-the-art flood risk simulator, estimate flood insurance premiums and household responses to flood risk and insurance incentives using a partial equilibrium model, and apply these parameters in a Computable General Equilibrium (CGE) model. We find that flood damages in 2050 lead to lower GDP as well as lower private and public welfare in all EU regions with particularly strong effects in South-Eastern and Southern EU as well as Romania and Poland. However, we also find that some insurance systems are better able to cope than others with issues posed by high or rapidly rising flood risk, particularly when considering private and public welfare measured as the consumption possibilities of each household. While the majority of EU regions currently maintain a private insurance system where uptake of coverage is optional and premiums are risk-reflective, the adverse macroeconomic impact of flood risk appears to be smaller when flood insurance is to some extent public, insurance purchase requirements are maintained, and risk-based pricing is limited. While no engagement in the insurance activities may seem as the cheapest option at the first sight for policy-makers, installing an adequate flood insurance mechanism will limit additional expenditures arising from households being insufficiently insured against damages.

The Italian case study of residential insurance against natural hazard, offers a particularly interesting example of "adaptation" mis incentive or "maladaptation". Notwithstanding the high exposure to natural hazards, property insurance coverage in Italy is low. The system of state *compensations* of disaster losses, which does not constitute a *duty-to-compensate* but connotes a long-establish customary practice, impedes private insurance markets. The *tripartite* mandatory nature of the last insurance scheme proposed that obliges property owners to underwrite insurance contracts, insurers to become part of the pool, and credit institutions to buy cat-bonds, does not abide with the rules of free internal market and disincentivize individual risk-sensitive behaviour. It embraces entirely solidarity and disowns individual or collective responsibility for risk. The abridged risk premiums determined according to sole typology of the buildings and the chosen level of protection does not

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encourage individual risk reduction. Finally, the proposed scheme cares little about the changing magnitude of risk from extreme weather and climate-related events, driven by societal and environmental changes. A smooth transition towards a reasonable risk pricing over a period of say thirty years or longer may send a signal to real estate market that delivers tangible outcomes gradually. Second, the risk and financial burden should be equally split among public and private entities engaged voluntarily in a partnership. The partnership itself should be based on sound risk assessment and every house owner or lessee should find it easy to access the information about the risk exposure of the owned or leased property. Third, the scheme should differentiate between levels of hazard exposure and, to the extent possible, pool the risk among the property owners within the same or similar categories of risk. Fourth, any duplicity between existing financial and economic instruments, including payments for water services or indivisible municipal services (the costs of which is recovered by property taxes or charges) and the envisaged scheme should be avoided. In the case of flood risk this may result in risk premium discounts proportionally to the amount of tax or service charges already paid.

Policy effectiveness in infrastructure, built environment, and transport for investments. Adaptation to coastal flooding will mainly be done by coastal protection. However, in areas that will not be protected (for instance sparsely populated areas) additional adaptation measures will have to be applied. In this sub-task additional adaptation to coastal flooding by flood proofing of infrastructure, by infrastructure elevation and by coastal retreat are analysed. The results show that at EU27-level coastal retreat is the most effective additional adaptation measure, followed by flood-proofing of infrastructure and infrastructure elevation.
For river flooding our analysis finds that expected damages in Europe can be reduced from €67 billion euros under the baseline flood protection standard assumptions to €27 billion if optimal flood protection standards (each states adapts in an economically optimal manner and invest today in the level of protection that would yield the highest net present value (NPV) over the twenty-first century) are implemented. Coastal flood risk may induce a tipping point due to concerns about the increasing flood risk. A case study analyses the socio-economic tipping point of a sudden drop in house prices for a stylized case with characteristics of Rotterdam. It is found that even in a city with very high initial protection, and with a strategy that dynamically adapts to the changing conditions, house price collapses may occur, especially in combination with the climate tipping point of accelerating sea level rise.

Policy effectiveness in non-market impacts: ecosystems and health for policy makers and research. For this sub-task, a case study was co-developed with policy makers. The case study reviewed the evidence, and undertook additional indicative analysis, to estimate the economic costs of climate change on non-market sectors in the UK for low and high warming pathways. It also undertook a review of adaptation

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costs and benefits to respond to these risks. The analysis considered 25 non-market risks, covering biodiversity and ecosystem services, as well as health and well-being. The analysis found that climate threats to non-market sectors could have very high aggregate economic costs, estimated at £billions/year in the UK, even by mid-century. The analysis also found a clear step change in costs under a 4°C versus a 2°C future: global mitigation will therefore have very large economic benefits in reducing the impacts to non-market sectors in the UK. The analysis also found an increased body of evidence that indicates high economic benefits from further adaptation in non-market sectors. It found that many early adaptation options in non-market sectors deliver high value for money, with positive benefit to cost ratios. The case study also provided some insights on policy needs, identifying that a much wider range of non-market risks were of concern for the government, which provides key information for future research in this area. The results of this case study have fed directly into the UK's published 3rd Climate Change Risk Assessment (CCRA3).

Policy effectiveness for policy makers. The final sub-task of this deliverable extends the analysis for each of the sectors in WP2, and brings together and assesses the potential benefits of mitigation and adaptation policy at the EU level. By comparing different RCP scenarios, the analysis shows that the annual economic benefits of mitigation to the EU are very large. However, these benefits mostly arise after 2050, and are most important in reducing the impacts of high warming scenarios. It is noted that large economic benefits arise for both market (e.g. coastal) and non-market (e.g. health) sectors. The implications of this is that even if the Paris Goals are achieved, the Economic Costs of Climate Change in the EU will be large – and furthermore – the impacts over the next 25 years can only be reduced significantly with adaptation. The task has also looked at the economic benefits of adaptation in Europe, estimating the reduction in impacts, and for several sectors, it has also looked at the costs of adaptation. The first finding is that adaptation can significantly reduce the economic costs of climate change and it is very effective both in the medium and longer term. The second finding is that adaptation shows high benefit to cost ratios: early adaptation therefore makes good economic sense, and can act complementarily to mitigation.

Peer-reviewed papers published as a result of this study

Bednar-Friedl, B., Knittel, N., Raich, J., Adams, K.M. (2022), Adaptation to transboundary climate risks in trade: Investigating actors and strategies for an emerging challenge, *WIRE Climate Change*, e758 (early access), https://doi.org/10.1002/wcc.758

Hochrainer-Stigler, S., Schinko, T., Hof, A., & Ward, P.J. (2021). Adaptive risk management strategies for governments under future climate and socioeconomic change: An application to riverine flood risk at the global

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level. *Environmental Science & Policy* 125, 10-20. https://10.1016/j.envsci.2021.08.010

Hudson, P., Botzen, W.J.W. & Aerts J.C.J.H. (2019). Flood insurance arrangements in the European Union for future flood risk under climate and socioeconomic change. *Global Environmental Change*, 58: 101966. https://doi.org/10.1016/j.gloenvcha.2019.101966

Hudson, P., De Ruig, L.T., de Ruiter, M.C., Kuik, O.J., Botzen, W.J.W., Le Den, X., Persson, M., Benoist A. & Nielsen, C.N. (2020). An assessment of best practices of extreme weather insurance and directions for a more resilient society. *Environmental Hazards*, 19:3, 301- 321. https://doi.org/10.1080/17477891.2019.1608148

Schinko, T., Drouet, L., Vrontisi, Z., Hof,A., Hinkel, J., Mochizuki, J., Bosetti, V., Fragkiadakis, K., van Vuuren, D. & Lincke, D. (2020). Economy-wide effects of coastal flooding due to sea level rise: a multi-model simultaneous treatment of mitigation, adaptation, and residual impacts. *Environmental Research Communications*, 2:1. https://doi.org/10.1088/2515-7620/ab6368

Tesselaar M, Botzen WJW, Haer T, Hudson P, Tiggeloven T, Aerts JCJH. (2020) Regional Inequalities in Flood Insurance Affordability and Uptake under Climate Change. *Sustainability* 12(20):8734. https://doi.org/10.3390/su12208734

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1. Introduction (lead: VU)

Objectives

This deliverable provides general information on policy effectiveness for European policy makers and includes a set of case studies examining policy effectiveness from sectoral and thematic perspectives. The sectoral approach has been facilitated by the co-development of the research case studies with the target groups of stakeholders from the thematic groups from WP1, namely policy making, business and investments.The sectoral studies use the analytical instruments developed in WPs 2 and 3, and takeinto account the risk preferences elicited in Task 4.1.

The table below shows the policies that have been addressed in each section of the report and which models are used to assess their effectiveness.

Topic	Section	Consortium partner	Policy	Short description of model approach
Policy effectiveness in agriculture	2.1	PIK	This study addresses the effectiveness of alternative policy scenarios in agriculture that are aligned with EU's climate targets	A combination of the global land systems model MAgPIE and the global multi-regional impact assessment model REMIND.
Policy effectiveness in industry and business	2.2	UNI-GRAZ, Ecologic	This study addresses policy effectiveness in industry and business, with a focus on adaptation measures for supply chains	Econometric analysis of the diversification of supply chains and adaptation pathways approach for supply chain networks in the North Sea Region

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Policy effectiveness in insurance	2.3, 2.4	IIASA, UNI-GRAZ, VU, CMCC	This study addresses the policy effectiveness of various flood insurance policies in EU countries and the UK on a macroeconomic scale and develops an example for Italy.	Integration of partial equilibrium model of flood insurance markets in the EU (the DIFI model) with a macroeconomic computable general equilibrium model (COIN-INT). The Italian case is analyzed qualitatively.
Policy effectiveness in infrastructure, built environment, and transport for investments	2.5	GCF, VU, DELTARES	This study addresses the policy effectiveness of various coastal and river flood adaptation strategies that include infrastructure, built environment and transportation.	Additional adaptation methods for coastal adaptation, integrated assessment model (CLIMRISK-RIVER) and a stylized case study simulating long-term adaptive behaviour in cities.
Policy effectiveness in non-market impacts: ecosystems and health for policy makers and research	2.6	PWA	This study reviewed the evidence, and undertook additional indicative analysis, to estimate the economic costs of climate change on non-market sectors in the UK for low and high warming	Review and additional indicative analysis in a co-development process with policy makers.

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			pathway to give insights into policy needs.	
Policy effectiveness for policy makers	2.7	PWA	This study presents results from each of the sectoral teams working in WPs 2 and 3, and assesses the potential effects of mitigation and adaptation policy for their sectoral modelling assessment.	Modeling approaches from WP2 and WP3 and additional analysis to express results in monetary terms, or to assess various policy options.

● 2. Sectoral assessments of policy effectiveness

○ 2.1 Policy effectiveness in agricultural business (Lead: PIK)

Introduction

With the Farm-to-Fork strategy, the European Commission gave itself a vision for a fair, healthy and environmentally friendly food system (EC 2021). In particular, the food system shall be aligned with the EUs ambitious targets to limit global warming to 1.5°, avoiding the most severe climate impacts. Europe's contribution to this target is the commitment to reduce GHG emissions by 55% in 2030 relative to 1990 and to become climate-neutral by 2050 (EC 2021). Yet, it still remains little analysed by which policy approaches these strategic aims shall be accomplished.

In our policy effectiveness assessment in agricultural business, we want to compare different policy approaches that are in line with these climate targets but that follow different policy paradigms. We distinguish six different paradigms: A market-

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oriented paradigm (S2), a behavioural paradigm (S3), a technology-oriented paradigm (S4), a policy-steered paradigm (S5), a mixed paradigm (S1) and the current paradigm (S6). Each of them combines a package of policy measures and a different degree of integration over different economic sectors.

We analyse the impact of these policy paradigms on different outcome-indicators for (a) business, (b) consumers and (c) the environment. Particular focus is placed on the assessment of international impacts of European policy, e.g. in respect to imports, exports, international land-use-change and greenhouse gas emission leakage.

Methodology

The study is conducted with the Model of Agricultural Production and its Impact on the Environment (MAgPIE), a modular open source framework for modeling global land-systems (Dietrich et al., 2019). For the purpose of this assessment that shall also cover cross-sectoral policy paradigms, MAgPIE was coupled with the REgional Model of INvestments and Development (REMIND). REMIND (Kriegler et al. 2017) is a global multi-regional model incorporating the economy, the climate system and a detailed representation of the energy sector. The dynamics within the macroeconomy and energy sector will however not be the focus of this assessment here, and shall rather help to have a more integrated view on the food system, in particular in respect to the usage of bioenergy for climate change mitigation.

Scenario setup

Six scenarios were designed for this analysis, which are all based on the same general pathway of socio-economic development, the SSP2 Shared Socioeconomic Pathway (O’Neill et al. 2015, Popp et al. 2017). The climate scenario in which globalwarming does not exceed 1.5°C is the RCP1.9 scenario which is stricter than the COACCH scenarios that were used in other parts of the COACCH project (DeliverableD1.5). The individual policy assumptions of the six scenarios are summarized in table
2.2.1. All scenarios are located in a global context where mitigation policies are adopted in all other world regions, too, reducing international leakage effects. The policies in other world regions do however not differ by scenario to allow for an isolation of the international effects of European policy.

Table 2.1.1: describes the scenario switches for the six scenarios which relate to the food system.

Theme	Description	Mixed	Market	Behavioural	Techno-logy	Policy Steered	Current
Efficiency	Nitrogen uptake efficiency on croplands in 2050	60%	60%	85%	85%	60%	85%

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	[percent]						
	Nitrogen uptake efficiency on pastures in 2050 [percent]	60%	60%	85%	85%	60%	85%
	Irrigation efficiency on croplands in 2050 [percent]	66%	66%	85%	85%	66%	85%
	Feeding efficiency improvement in livestock and increased recycling rates	30%	30%	40%	40%	30%	40%
	Upper bound for non-CO2 GHG price (US$ per tC)	unlimited	unlimited	500	500	unlimited	500
Protection	Forest protection	eu-wide	eu-wide	eu-wide	eu-wide	eu-wide	eu-wide
	maximum global afforestation [mio Ha]	500	500	unlimited	unlimited	500	unlimited
	Environmental flow protection for rivers, limiting irrigation water	yes	yes	no	no	yes	no
Demand	Dietary change towards plant-based healthy diets	EAT-Lancet diet	no specific change	EAT-Lancet diet	no specific change	no specific change	no specific change
	Food waste in households	20%	30%	20%	30%	30%	30%
Technology	Carbon Capture and Storage capacity	max 750 Mt CO2/a	max 750 Mt CO2/a	max 150 Mt CO2/a	max 750 Mt CO2/a	max 150 Mt CO2/a	max 150 Mt CO2/a

Table 2.1.1: Scenario assumptions for the six policy paradigm scenarios.

Additionally to the scenario switches described here, two scenario drivers are endogenous the REMIND-MAgPIE coupling and differ by scenario: a) The GHG tax rate, which is the consequence of the development of all economic sectors, as well as the switches for an upper-bound of GHG prices, and (b) the demand for bioenergy, which is the consequence of the developments in the energy sector, the scarcity and opportunity costs in the land system as well as the acceptance of Carbon Capture and Storage to sequester the carbon from combusted bioenergy. The resulting tax rates and bioenergy demand are displayed in Figure 2.1.1.

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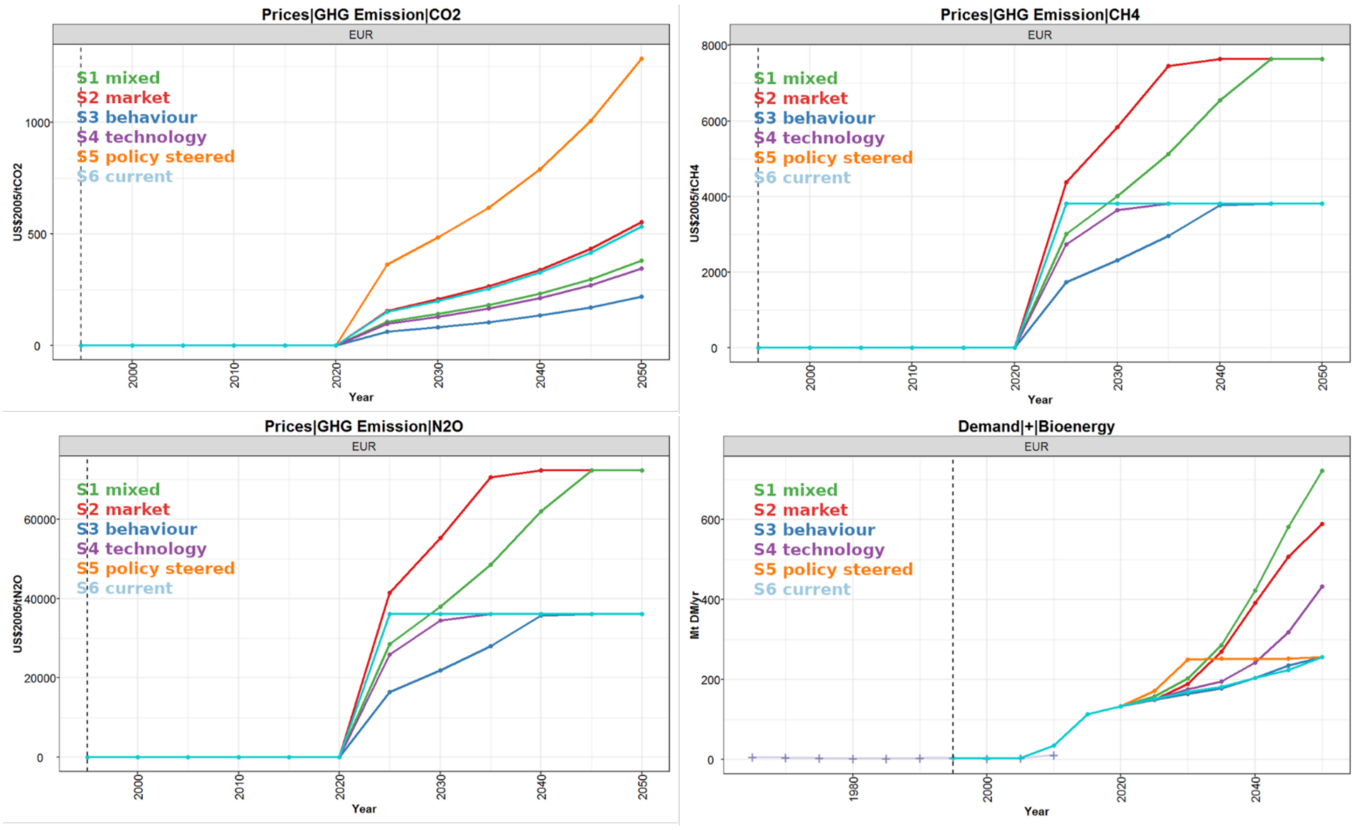

Figure 2.1.1: Scenario inputs from the coupled REMIND-MAgPIE framework for CH4 and N2O price in agriculture and the CO2 price for landuse change emissions, as well as the bioenergy demand from the energy sector.

Results

Agricultural Business

We find that the different policies have rather different outcomes in respect to crop livestock and bioenergy (miscanthus and fast-growing trees) production (Figure 2.1.2) and in respect to the net-trade of crop livestock and secondary products like oilcakes (2.1.3). The two scenarios with dietary change (S1+S3) show a decline in European livestock production as exports do not increase when demand decreases. In line with the reduction of livestock products, the import of secondary products such as oilcakes, which are primarily used as livestock feed, declines in these two scenarios. Also normal crop production is lower than in other scenarios as feed demand is reduced despite an increase of plant-based food demand.

The other scenarios mainly differ in respect to the production of bioenergy crops. Here the scenarios without an upper limit for CCS Technology have a higher adoption of bioenergy crops. The highest production in all three categories is

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achieved in the market scenario (S2) with high demand and lower efficiency improvements in production.

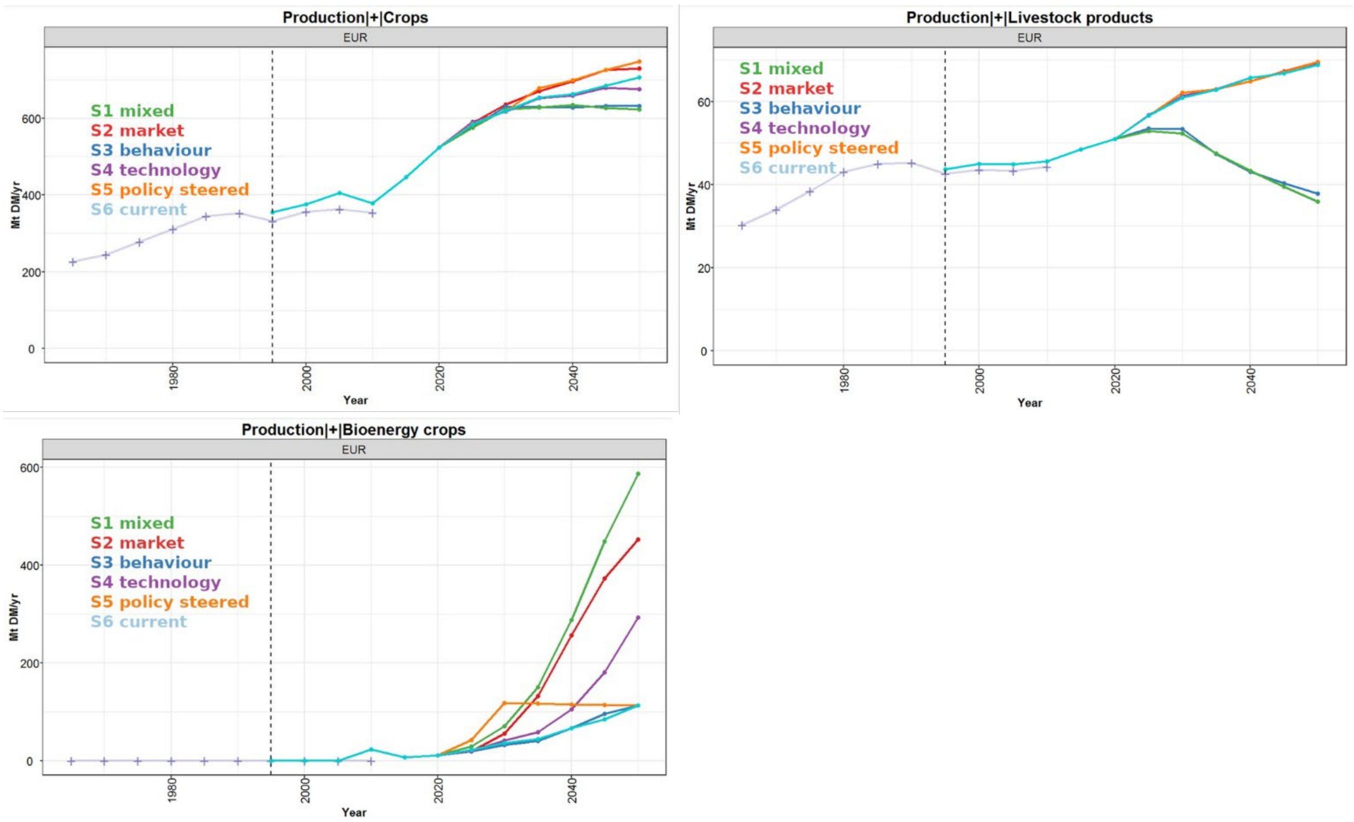
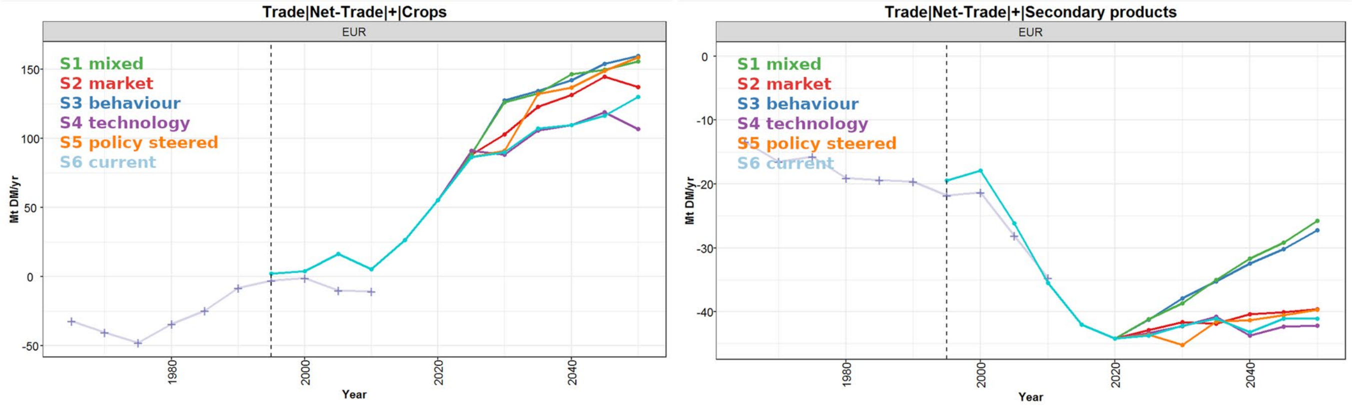


Figure 2.1.2: Production of crops, livestock products and 2nd generation bioenergy crops (miscanthus or fast growing trees) for the six policy scenarios.



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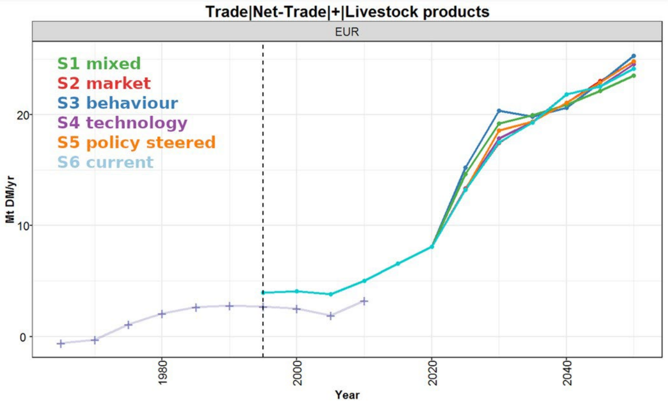

Figure 2.1.3: Net-Trade (exports-imports) for crops, secondary products (mostly oilcakes) and livestock products from Europe to non-European world regions for the six policy scenarios.

Consumers

Food demand remains rather stable in normal scenarios, and shows a strongly declining trend for livestock products in the behavioural change scenario (S3) and the mixed scenario (S1). In line with this development, also food expenditure declines (please note that this is the expenditure for raw agricultural commodities, not final consumer expenditures that would also include marketing and processing costs) by roughly 50%. In general, food expenditures for raw commodities in Europe are however so low that they have no major impacts on disposable income. Also, our simulations suggest that the different European policies do not have a major impact on food prices and expenditure in other world regions.

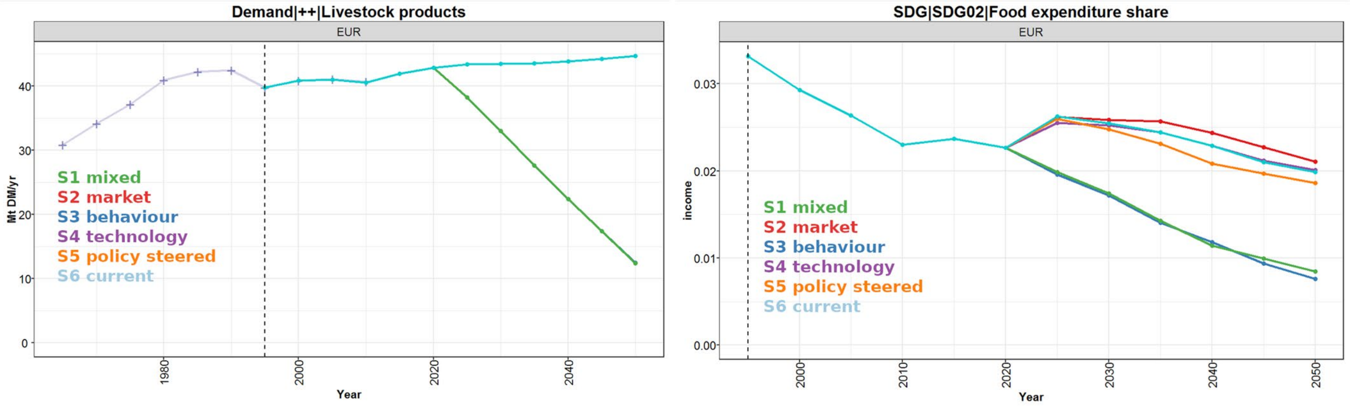

Figure 2.1.4: Demand for livestock products and food expenditures share (value of expenditure for raw agricultural production per capita divided by average per-capita income) for the six policy scenarios.

Environment

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Land use change is also affected by European policies. In Europe, the decline in livestock demand in S1 and S3 lead to a decline in pasture areas. These freed areas are partially converted to croplands. At the same time S1 and S3 do not show an increase in crop production; rather the intensity of crop production declines, with lower yield increase rates than in other scenarios. This goes along a sustainable extensification.

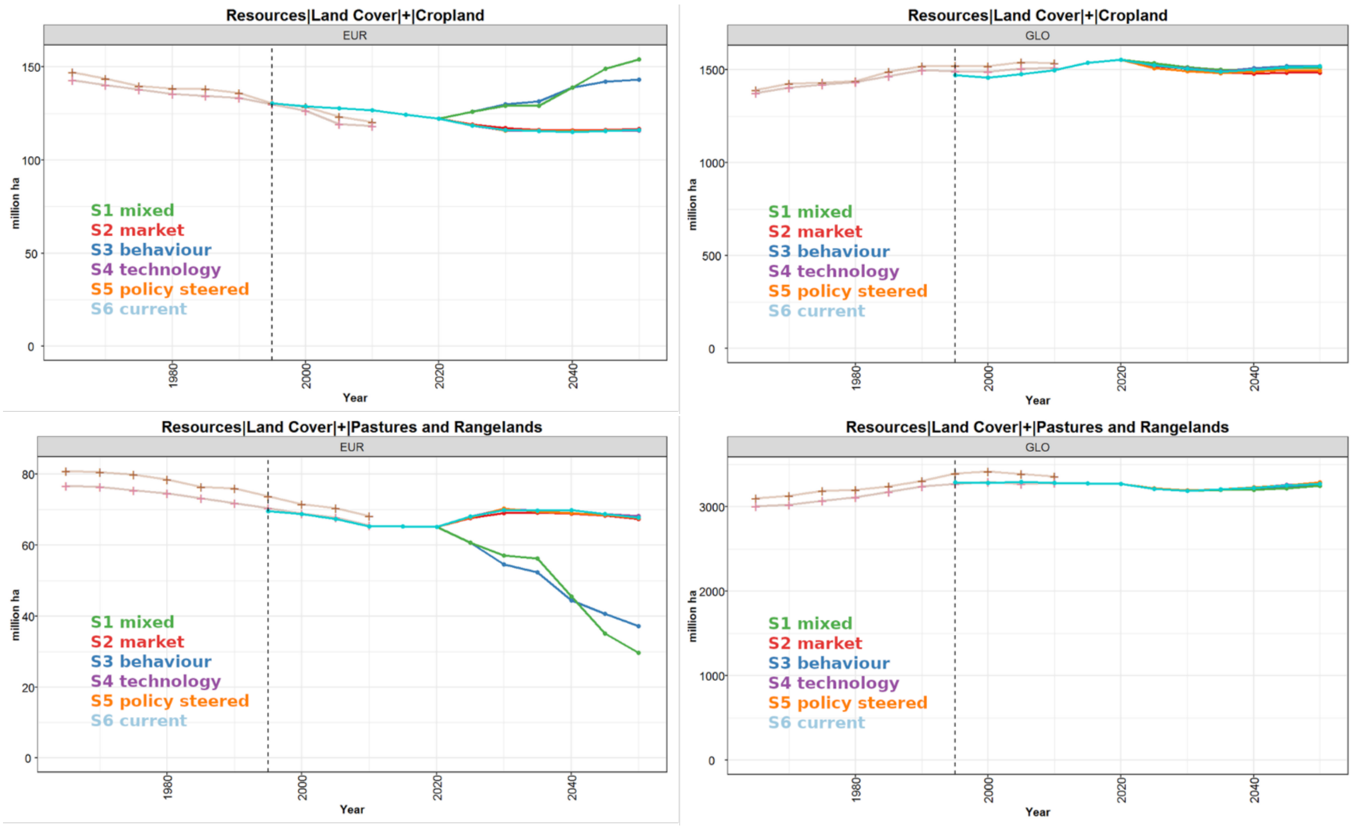

Figure 2.1.5: Land use expansion or contraction of cropland (upper row) and pastures (lower row) in Europe (left columns) and the world (right columns) for the 6 policy scenarios.

CH4 emission estimates are higher than in the historical data due to a different estimation method (IPCC Tier-1 in historical estimates vs Tier-2 in projections). CH4 emissions decline in the scenarios of reduced livestock demand (S1+S3), but are relatively similar in all other scenarios. On a global scale, European CH4 emissions are of relatively small magnitude such that the global totals are little affected.

N2O emissions most strongly decline in the mixed scenario which assumes both high efficiency improvements and a changed demand. S2,3,4, also show a similar effect despite S3 reducing emissions rather with changed consumer demand patterns while S3 and S4 have higher production efficiencies. S5 and S6 here show the largest reductions.

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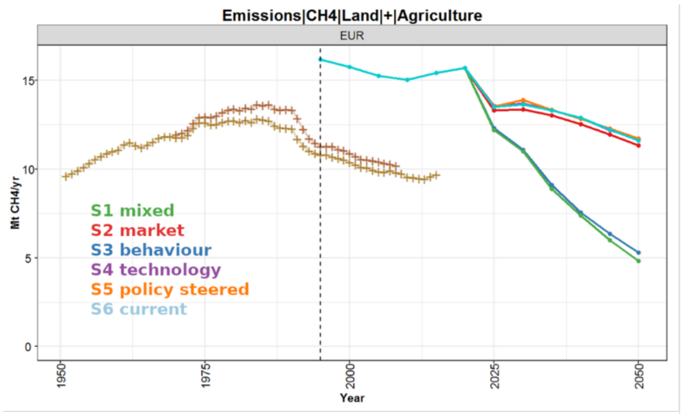
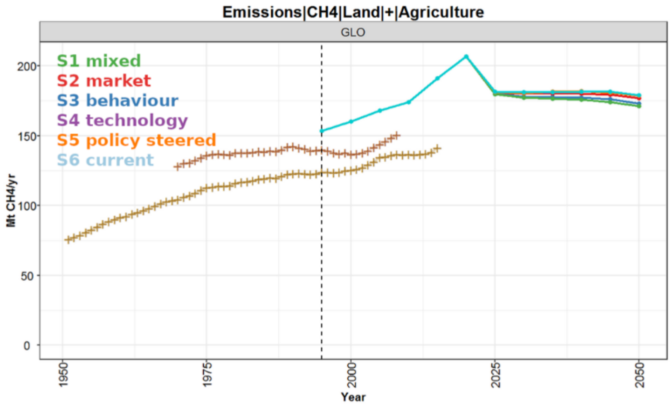
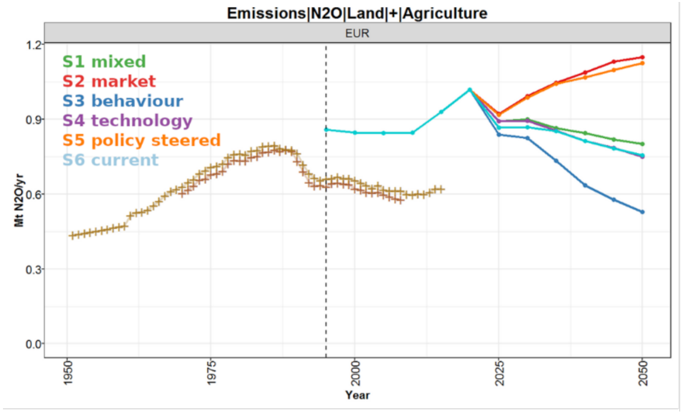
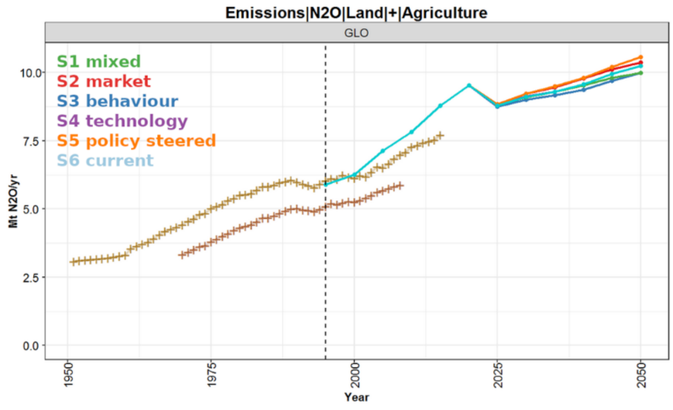
CO2 is by tendency sequestered in Europe, as agricultural areas were abandoned and continue to do so in many scenarios, and forests and natural vegetation is growing in these areas, sequestering carbon. Interestingly, the diet-change scenario has slightly lower CO2 sequestration rate, despite the strongly reduced pasture areas. The reason here is that parts of the abandoned pastures are instead being used as croplands, leading to a decline in soil organic matter and thereby to a release of CO2 emissions. On a global scale, the difference between the analysed European Policies has no substantial effect on cumulative CO2 emissions. The reason is our scenario assumption that in all analysed scenarios, the non-European regions also implemented a carbon price in line with a strict climate target; this prevents carbon leakage of policies into other world regions.









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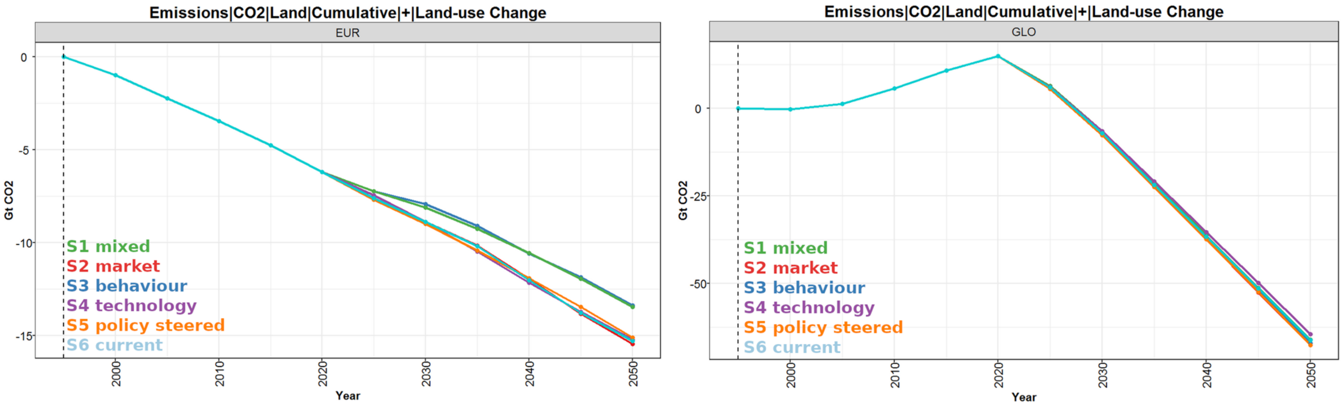

Figure 2.1.6: Emissions of CH4 and N2O for the 6 policy scenarios in Europe (left) and the world (right).

With respect to nitrogen pollution (Figure 2.1.7), nitrogen surpluses change in the mixed, market and technology scenarios (S1,2,4), while they increase in the other three scenarios.

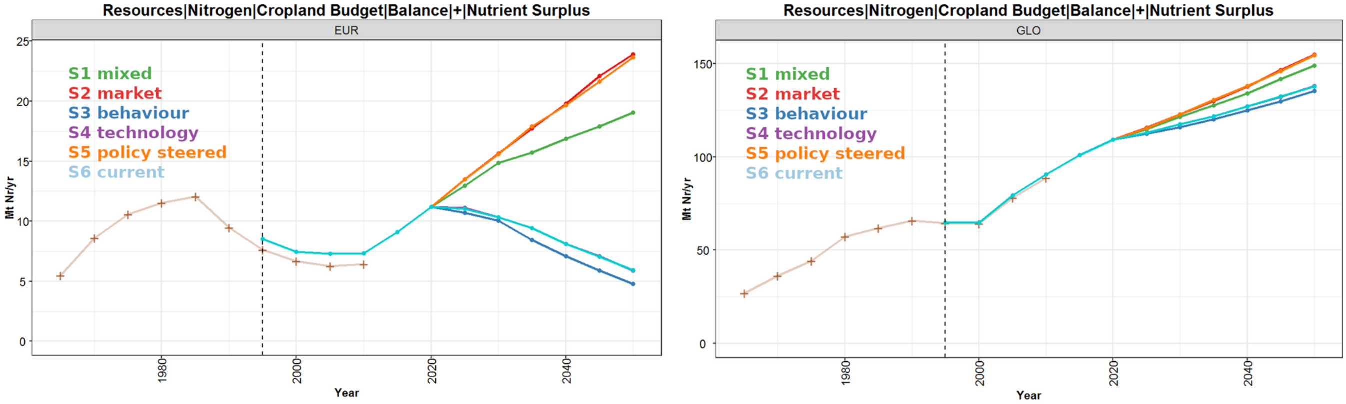

Figure 2.1.7: Nitrogen surplus on croplands (calculated as organic and inorganic N inputs minus the removal in the form of harvested crops and residues) in Mt N for the 6 policy scenarios.

○ 2.2 Policy effectiveness in industry and business (Lead: UNIGRAZ)

This section analyses climate change risks and adaptation for industry and business, by first giving an overview on risks and adaptation for the manufacturing industry (Section 2.2.1). Section 2.2.2 looks into risks from supply chain disruptions and implications for adaptation. Section 2.2.3 assesses adaptation pathways for European seaports.

2.2.1 Climate change adaptation in industry – an overview of options and responsibilities

Introduction

It is evident that companies increasingly recognise the risks posed by climate change impacts: in 2015, 407 Fortune 500 companies listed 1016 physical risks to the Carbon Disclosure Project (UN Global Compact *et al* 2015). However, the Global Climate Action Playbook 2018, published by the UN Global Compact and World Resources Institute, highlights the continuing imbalance between mitigation and adaptation efforts in the private sector (UN Global Compact and WRI 2018). While more than 300 companies have made emission reduction commitments, only "a few dozen" were identified as having made commitments to evaluating and ensuring water availability, as one example of adaptation. This demonstrates the need for continued focus within the industrial sector on adaptation as an important and necessary complement to mitigation.

Many companies are aware of physical climate risks but have not yet developed adaptation strategies, plans or actions (UN Global Compact and UNEP 2012). However, a number of case studies on businesses designing climate adaptation actions and their implementation experiences have been published (e.g. UN Global Compact and UNEP 2012, UN Global Compact *et al* 2015). In these reports, climate adaptation is discussed from a risk perspective but also as a potential business opportunity (Baglee *et al* 2015, UN Global Compact and UNEP 2012, UN Global Compact *et al* 2015). While case studies and best practice examples may be considered a vital source of information in this respect, this section presents a comprehensive overview of the state of scientific literature on climate adaptation in the manufacturing industry, acting as a resource for scientists, businesses and policy makers, to increase resilience in the face of climate change impacts.

While the adaptation literature in general has increased strongly during the last decade (Berrang-Ford *et al* 2011, Biesbroek *et al* 2018, Palutikof *et al* 2019), only a comparatively small body of literature focuses on adaptation in the manufacturing industry. This can be attributed to two primary causes. Firstly, the manufacturing industry is not considered to be as climate sensitive as sectors depending directly on weather conditions like the agricultural sector. Yet, the manufacturing industry contributes strongly to employment and economic growth in industrialized countries. Recent evidence for the UK therefore identifies the manufacturing industry as one of the highly exposed sectors (Baglee *et al* 2015). Secondly, industrial companies consider mitigation efforts and carbon management as more important to their businesses resulting in a similar imbalance in the literature (Kolk and Pinkse 2004, Goldstein *et al* 2019). However, business and industry initiatives such as the UN Global Compact, the World Business Council for Sustainable Development or the Carbon Disclosure Project have recently pointed towards the relevance of physical climate risks (UN Global

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Compact and UNEP 2012, BSR 2015, 2016, TSFR 2017, World Business Council for Sustainable Development 2008, OECD 2015).

We review literature on adaptation action by the manufacturing industry as a response to physical climate risks, and potential drivers and barriers in this respect. In particular, we address the following research questions:

- To which physical climate change risks does the manufacturing industry adapt? How are production processes, management, supply chains and sales markets potentially affected by these risks?
- Which measures do firms in the manufacturing industry apply to adapt to climate change? Do they act proactively or reactively?
- Which drivers and barriers exist in the uptake of adaptation actions? What are the main internal and external factors influencing a firm's adaptation decision?

Methodology

The literature search was conducted on three scientific literature databases: Web of Science, Scopus, and EBSCO Business Premier. While Web of Science and Scopus are the most widespread multidisciplinary scientific databases (Chadegani *et al* 2013), EBSCO Business Premier is focused on the business and management literature. Figure 2.2.1 shows the search query used.

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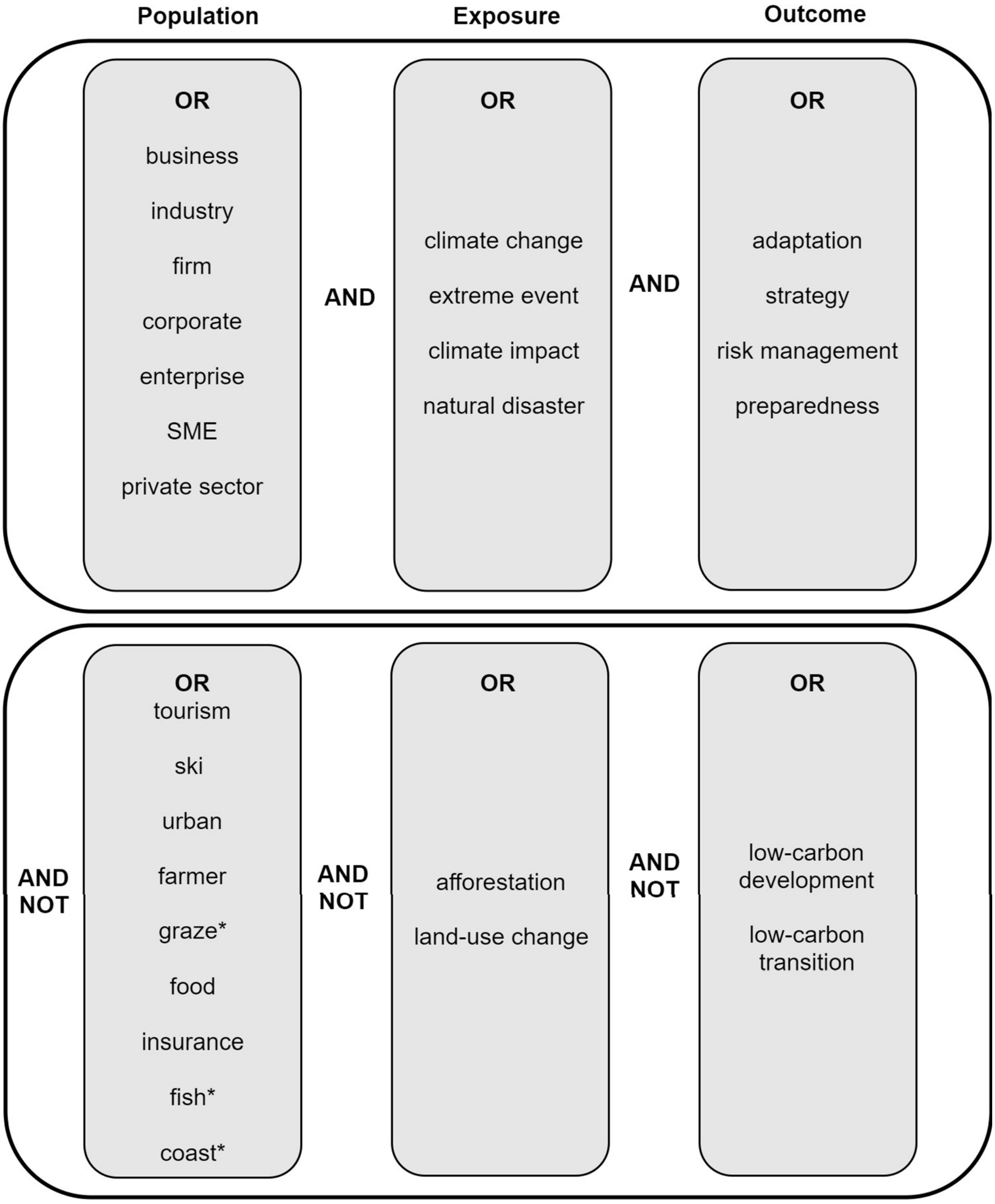

Figure 2.2.1: Search query performed in Web of Science, Scopus, as well as EBSCO Business Premier

As subject areas of the respective databases we selected business and economics, as well as other relevant subject areas, such as health, pharmaceuticals, chemistry and engineering. As adaptation is a rather recent topic in industry and business, we limited the search string to literature from 2007 onward, corresponding to the fifth and sixth IPCC assessment cycles.

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The search query produced a total number of 5918 papers. Due to the inconsistent use of the term adaptation in this strand of literature, and because of narrow sectoral boundaries, additional restrictions could not be implemented in the search query as these could be related to adaptation options within industry (e.g. water, energy, resources). The screening of titles and abstracts was conducted by four researchers, with two researchers screening each paper. Inclusion and exclusion criteria (Table 2.2.1) were elaborated iteratively, verifying stepwise that only irrelevant search results were excluded. Inconsistencies were resolved by discussing the relevant papers, as well as the inclusion and exclusion criteria in regular meetings of the total group, where any remaining ambiguities on the decision specific papers were resolved . This step resulted in 79 potentially relevant papers, whereof 9 papers could not be found or were inaccessible. This reduced the number of potentially relevant papers to 70.

Table 2.2.1: Inclusion and exclusion criteria in the screening process

Focus	**Inclusion criteria**	**Exclusion criteria**
Thematic	Adaptation	Mitigation or “adaptation” used in other context
Scope	Original research on adaptation, i.e. adaptation evaluated in the main part of the paper	Adaptation mentioned in introduction or conclusion only
Sectoral	All industrial sectors	Other sectors (agriculture, forestry, water, food, finance, construction, resource extraction, utilities, services, etc.)
Actor	Private enterprises, i.e. Firm level or sector(s)	Public authorities, cities
Method	Empirical, case study, survey, interviews, simulation	Conceptual, literature review, analytical models

After screening the title and abstract, some papers could not be systematically eliminated. A quick reading of the full text was then used for the final selection of papers. If adaptation was not analysed or assessed in the main part of the paper, but e.g. only mentioned in the introduction or the conclusion, the paper was excluded. Moreover, 6 review papers and 26 conceptual papers, that could not be identified as such from

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reading the abstract, were eliminated. This final step of the screening process resulted in a final number of 38 papers.

All articles were coded in MAXDQA following an iterative, combined deductive-inductive procedure (Table 2.2.2). While for most categories relevant codes for classification could be selected, in some categories open answers were used (e.g. for drivers and barriers). For the data extraction, the papers were randomly assigned to the four researchers. Each paper was coded by one researcher who extracted the relevant text and mapped it to the predefined codes for all categories. To ensure consistency, a second researcher then compared the codings within a category and ensured consistency in codings across all papers.

Table 2.2.2: Categories used in data extraction

Dimension	**Categories**
Industrial sector	NACE codes 20-33; not specified
Firm size	SME, large, MNE, cluster, not specified
Country/region	OECD, non-OECD, Asia, Africa, America, Australia, Europe,
Data used	Official data, CDP questionnaire, survey, literature review
Method	individual textual description
Physical climate risks	Extreme precipitation, droughts, heat / heat waves, storm, coastal flooding, sea-level rise, riverine flooding, other, not specified
Time frame	Climate: RCP2.6, 4.5, 6.0, 8.5; not specified Economy: SSP1-SSP5; not specified; observed impacts; projected risks (short, medium, long term)
Potential impact on industry	Impact on production process (stock- and production material, production- and logistics facilities, economic performance and costs, employees, IT and communication) , impact on management, supply chain and procurement risks (suppliers, transport infrastructure, water supply, energy supply), demand risks/changes in sales markets, not specified

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Adaptation actions	Soft (risk management & planning, capacity building & human resources, disaster preparedness plans, information & R&D warning & observing systems, supply chain, finance, policy), hard (infrastructure design or adjustments, products, utility/infrastructure strategies, transportation), green/ecosystem based, not specified>
Adaptation status	Implemented, planned, suggested
Drivers and barriers to adaptation	Verbal

A comprehensive representation of physical risks, impacts on industry and adaptation actions by paper can be found in the Appendix (Table A.1).

Results

Physical climate risks and impacts on industry

Physical risks are those risks that result from the physical impacts of climate change due to either extreme weather and other events such as flooding, tropical storms and extreme precipitation, or more gradual climatic changes such as sea level rise and temperature increase (TCFD 2017). Table 2.2.3 shows which physical risks and associated potential impacts on industry are described in each of the 38 papers. The most frequent physical climate risks identified are droughts and water scarcity (39%), followed by extreme heat and heatwaves (37%), and storms such as hurricanes, typhoons, and tornados (34%). 37% of papers do not specify the type of climate risks but speak of climate change, climate variability, and extreme weather. Riverine floodingand coastal flooding due to sea level rise are identified in 26% and 16% of the papers. 18% of the papers mention additional risks such as changes in rainfall patterns, cold waves and heavy snow. A handful of quantitative papers, using data from the Carbon Disclosure Project or other company surveys, compare the relative importance of theserisks based on a global scale. They find that changes in extreme precipitation and droughts are most relevant for companies in the manufacturing industry, as well as heat,tropical cyclones and changes in precipitation patterns (Gasbarro *et al* 2017, Goldstein *et al* 2019). While sea level rise and flooding are identified as a comparatively smaller risk today, they are seen as increasingly relevant in the future (Kang *et al* 2017, Sakhel 2017).

A popular approach to group climate change impacts on industry is to differentiate them along the stages of the value chain (e.g. Christopher and Peck 2004, Lühr *et al* 2014, Meinel and Abegg 2017, Goldstein *et al* 2019). The Carbon Disclosure Project’s Climate questionnaire of 2018 (CDP 2019) distinguishes risks for direct operations, for the supply chain, and for customers. In addition, Lühr *et al* (2014) and Goldstein *et al* (2019) separate the risks for a company’s internal operations into impacts on the production

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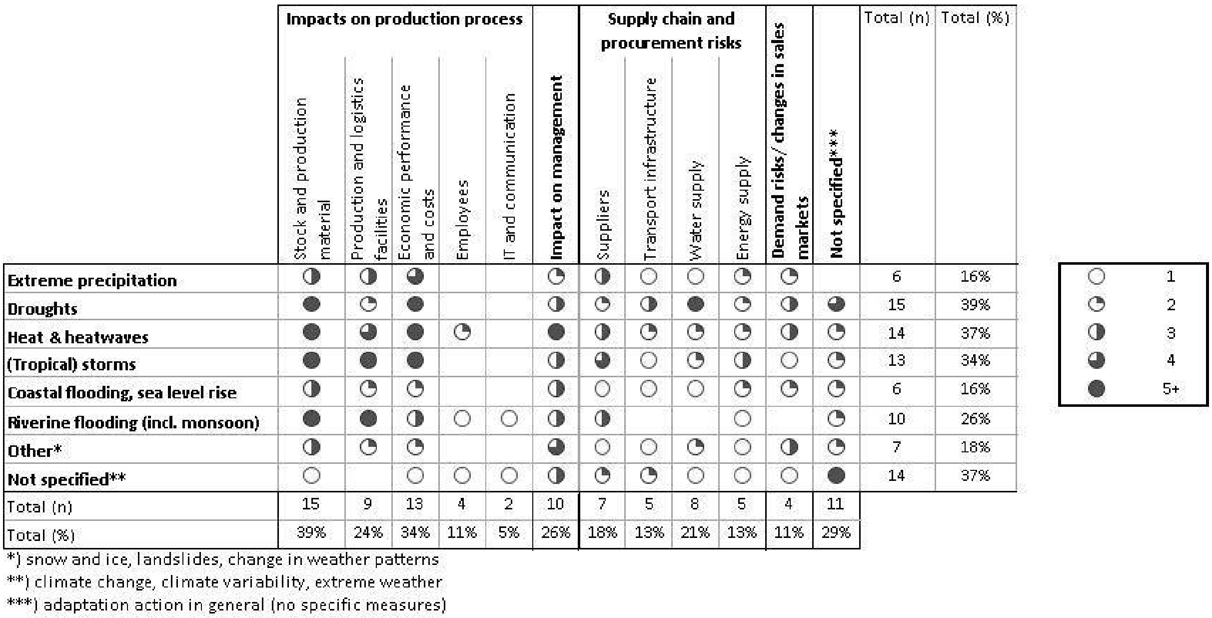
process and on management. We therefore distinguish twelve impact categories which we cluster in four groups, as listed in Table 2.2.3.



	Impacts on production process					**Impact on management**	**Supply chain and procurement risks**				**Demand risks/ changes in sales markets**	**Not specified*****	Total (n)	Total (%)
	Stock and production material	Production and logistics facilities	Economic performance and costs	Employees	IT and communication		Suppliers	Transport infrastructure	Water supply	Energy supply				
Extreme precipitation	◑	◑	◕			◔	◑	○	○	◔	◔		6	16%
Droughts	●	◔	●			◑	◔	◑	●	◔	◑	◕	15	39%
Heat & heatwaves	●	◕	●	◔		●	◑	◔	◔	◔	◑	◔	14	37%
(Tropical) storms	●	●	●			◑	◕	○	◔	◑	○	◔	13	34%
Coastal flooding, sea level rise	◑	◔	◔			◑	○	○	○	◔	◔	◔	6	16%
Riverine flooding (incl. monsoon)	●	●	◑	○	○	◑	◑			○		◔	10	26%
Other*	◑	◔	◔			◕	○	○	◔	○	◑	◔	7	18%
Not specified**	○		○	○	○	◑	◔	◔	○	○	○	●	14	37%
Total (n)	15	9	13	4	2	10	7	5	8	5	4	11		
Total (%)	39%	24%	34%	11%	5%	26%	18%	13%	21%	13%	11%	29%		

*) snow and ice, landslides, change in weather patterns
**) climate change, climate variability, extreme weather
***) adaptation action in general (no specific measures)

○	1
◔	2
◑	3
◕	4
●	5+

Table 2.2.3: Frequency of papers addressing physical climate risks and potential impacts on industry. Papers addressing multiple climate risks or impact categories are only counted once in the total number (*n*) in each category.

In terms of frequency, three of the four most relevant impact categories are related to production processes: damages to production stock and material (39%), reductions in economic performance and increased production costs (34%), and damages to production and logistics facilities (24%). Damages to production stock and material are most often mentioned in the context of drought (Scholten *et al* 2011, Hossain and As-Saber 2013a, Scholten *et al* 2014, Tan *et al* 2016, Chen *et al* 2017), heat (Hossain and As-Saber 2013a, Chen and Yang 2019) and storm (Jiang *et al* 2016, Aguinaldo *et al* 2019, Misuri *et al* 2019), as well as coastal and riverine flooding (Ryu *et al* 2017, Harries *et al* 2018). For example, the pharmaceutical industry can be affected by water scarcity and poor water quality in the manufacturing of antibiotics and other drugs (Hossain and As-Saber 2013a). Humidity due to flooding can affect the proper functioning of machinery e.g. in the electronics industry (Ryu *et al* 2017). Drought may require shutting down production in the chemical industry because of water rationing (Chen *et al* 2017). Industries deploying just-in-time production are particularly affected by shortages in raw materials and other inputs (Meinel and Abegg 2017).

Economic performance can be reduced because of a decrease in earnings and increased costs, as a result of damaged assets, and operational disruptions (Hardisty 2009, Reddy *et al* 2015, Gasbarro *et al* 2017, Crick *et al* 2018, Huang *et al* 2018, Halkos *et al* 2018, Goldstein *et al* 2019). This impact on economic performance has been analysed for increased temperature (Zhang *et al* 2018, Chen and Yang 2019), droughts (Jeßberger *et*

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al 2010, Santos *et al* 2014), tropical storms and flooding (Aguinaldo *et al* 2019, Jiang *et al* 2016), as well as for compound climate risk measures (Huang *et al* 2018). For instance, storm surges like those after typhoon Vera in Japan in 1959 could lead to substantial property and business interruption losses (Jiang *et al* 2016). In the worst case, reduced profitability may result in an inability to do business, but adaptation is found to substantially reduce these impacts (Reddy *et al* 2015, Jiang *et al* 2016).

Damages to production and logistics facilities are mentioned most often for storms (Jiang *et al* 2016, Misuri *et al* 2019) and riverine flooding (Abe and Ye 2013, Ryu *et al* 2017, Harries *et al* 2018). In the chemical industry, tropical storms and flooding can necessitate temporal production shutdown when facing the risk of inundation of production plants and wastewater systems (Chen *et al* 2017, Ryu *et al* 2017, Misuri *et al* 2019). Severe storm and flooding events may also result in property damage and loss (Jiang *et al* 2016).

In addition to production processes, employees may also be affected by climate change impacts. Heat induces heat stress, particularly for outdoor workers (Meinel and Abegg 2017, Lundgren-Kownacki *et al* 2018, Chen and Yang 2019). For China, Chen and Yang (2019) find that heat-induced productivity losses in the rubber industry are among the top three within all industrial sectors. Storms and flooding, such as the flooding in Thailand in 2011, led to business interruptions and consequent layoffs of employees and voluntary retirements (Abe and Ye 2013).

Impacts on management are identified as relevant in 26% of the papers. Business management can be affected in several dimensions: reduced market valuation (Gasbarro *et al* 2017); reduced access to capital (Gasbarro *et al* 2017, Meinel and Abegg 2017), particularly for SMEs (Davlasheridze and Geylani 2017); change in insurance premiums (Hardisty 2009, Abe and Ye 2013, Berkhout 2014); change in business strategy (Tenggren *et al* 2019); temporal relocation of production (Abe and Ye 2013); contractual penalties for delays (Meinel and Abegg 2017); changes in debt levels (Huang *et al* 2018); and potential reputational risk (Sakhel 2017). Finally, disasters may also pose business opportunities such as for the pharmaceutical industry in the form of additional demand for medication (Hossain and As-Saber 2013a).

Supply chain and procurement risks are mentioned only in a smaller number of papers, in which risks of default of suppliers are mentioned most often (18% of papers). Extreme precipitation, storms and riverine flooding are seen as climatic causes of supplierdefault, as exemplified by the floods in Thailand in 2011 which led to a default of car parts suppliers, with global consequences for the car manufacturing industry, and a global shortage of hard disk drives (Abe and Ye 2013, Goldstein *et al* 2019). Disruptionsof supply chain networks may imply that prices of essential production materials increase or that these inputs, such as raw materials, are becoming temporarily unavailable (Meinel and Abegg 2017, Misuri *et al* 2019, Tenggren *et al* 2019). Moreover,low water on rivers can impair the delivery of mass cargo by inland shipping to automotive industries and other just-in-time producing industries (Scholten *et al* 2011).

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Insufficient water supply, e.g. for the cooling of production processes (Hardisty 2009, Santos *et al* 2014, Alkaya *et al* 2015, Reddy *et al* 2015, Chen *et al* 2017), and disruptions of gas and electricity supply (Meinel and Abegg 2017, Ryu *et al* 2017, Misuri *et al* 2019) pose another potential risk to the manufacturing industry.

Finally, risks on demand and in sales markets can emerge from changes in customer preferences and reputational risks (Berkhout 2014, Sakhel 2017), leading to reduced demand for goods and services (Gasbarro *et al* 2017); but demand for specific goods such as medical products can eventually increase after a climatic event (Hossain and As-Saber 2013a).

How does the manufacturing industry adapt to climate change?

Adaptation measures are diverse and possess various characteristics along which they can be classified: public or private, proactive or reactive, autonomous, planned or natural, or distinguishing between the different types of adaptation measures. In its fifth Assessment Report, the IPCC broadly classifies adaptation options into structural or physical measures that are usually capital-intensive; social measures consisting of educational, behavioural or informational actions, and institutional measures including policies and regulations (Noble *et al* 2014). More recently, ecosystem-based adaptation has been added to this list (Cohen-Shacham *et al* 2016). Another common categorisation, that we follow in the present study, is the distinction between soft, hard and ecosystem-based adaptation (Isoard *et al* 2010). Soft approaches focus on capacity building and information, such as early warning systems and education or training of staff members. Hard options use specific technologies and are primarily involved in technical constructions. Ecosystem-based adaptation comprises measures to preserve, restore or enhance ecosystems and its services and shares features from both soft and hard adaptation.

In total, we identified 174 individual adaptation measures. While one paper can contain multiple measures and each measure can be attributed to various adaptation categories, it is accounted for only once per category even when mentioned repeatedly in the same paper. We find that our literature sample contains a large share of soft measures (62%), followed by hard adaptation measures (28%) and a small share of ecosystem-based adaptation measures (10%) (Figure 2.2.2).

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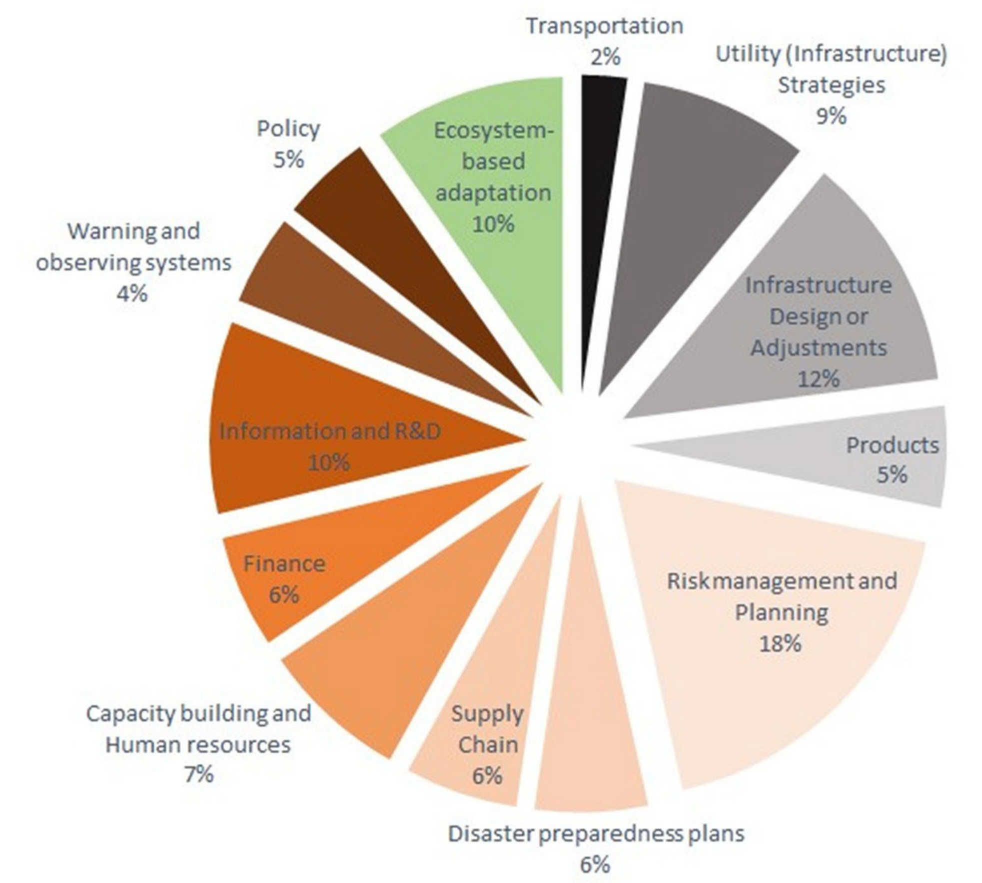

Figure 2.2.2: Adaptation measures by subtypes of soft (orange), hard (grey) and ecosystem-based (green) (100% refers to all 174 adaptation measures identified in the literature sample)

About half of the papers considered in this review (55%) cover either soft or hard adaptation measures only, while the other 45% mention both types of measures. Ecosystem-based adaptation measures, covered in merely four papers, are always mentioned jointly with other adaptation options, indicating that they are used as complementary actions in e.g. rainwater management or watershed protection.

The diversity of soft adaptation measures

As observed by Goldstein *et al* (2019) and others, soft measures are the most prominent choice when addressing climate change. While hard options require specificity according to business characteristics and a company's production site and location, soft measures can be universally useful. What is hidden under the heading of soft measures, however, is just as manifold. Based on our analysis and the 'themes' proposed by Goldstein *et al* (2019), we define the following categories of soft adaptation: *risk management and planning* (including disaster preparedness plans), *supply chain measures, capacity building and human resources, finance measures, information and R&D, warning and observing systems* and *policy*.

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Risk management and planning measures is a broad category that entails general business continuity planning, collaboration with partners, diversification of assets, locations, products, etc., new construction standards, incorporating climate into long-term planning, not building in the floodplain, back-up power installation, and moving critical equipment to higher ground or back-up facilities. *Supply chain measures* clearly target supply chain management such as shifting production location or inventory management. Measures in the category *capacity building and human resources* include employee education and training aiming at a behavioural change, supplier relationships, community engagement or general marketing. *Finance measures* consist of insurance and other risk transfer mechanisms, adjustments of credit ratings or simply factoring climate into investment decisions. *Information and R&D* actions contain the collection and sharing of information and research and development of climate adaptation related topics. *Warning and observing systems* include the ongoing monitoring and surveillance of relevant climate risks and the installation, provision or use of early warning systems. Finally, *policy measures* are public actions by which private climate adaptation is incentivized or enabled such as financial support or provision of information or other public goods.

Figure 2.2.3: Soft adaptation measures (font size indicates relative prominence of the adaptation category)

Figure 2.2.3 shows that among the literature we considered, risk management and planning is the most common measure of all soft adaptation categories (mentioned in

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37% of the papers; Table 2.2.4). Adding the specific measure of developing disaster preparedness plans increases the proportion to 53% of papers. Thus, more than half of all papers entail at least one measure that contains a planning or risk management element.[2] While risk management and planning entail various measures such as the availability of slack resources (Meinel and Abegg 2017), enlargement of storage (Scholten *et al* 2014) or managing water consumption (Santos *et al* 2014), the ultimate goal is to maintain “business continuity through disruptive climatic events” (Goldstein *et al* 2019, p 19).

Almost a fourth of all papers (24%) identify adaptation actions that aim to build capacity and interact with human resources (Abe and Ye 2013, Jacob *et al* 2015, Linnenluecke *et al* 2015, Kang *et al* 2017, Crick *et al* 2018, Green *et al* 2018, Zhang *et al* 2018, Aguinaldo *et al* 2019, Karman 2019). While most of these measures comprise education and training within a company, this category also includes staff redundancies as reactive adaptation in the aftermath of a disaster (Crick *et al* 2018), or the increase of labour in response to reductions of labour productivity caused by rising temperature in Chinese manufacturing plants (Zhang *et al* 2018).

Another popular approach to handle uncertainty in the context of climate change is to incorporate relevant information in decision-making processes and to foster R&D in the respective areas (24% of papers). On a general level, Jacob *et al* (2015, p 1212) mention the different options of “internal R&D in the firm or organization”, “external R&D” or the “acquisition of other exterior knowledge”. In the context of the development of a climate-resilient industrial park, Aguinaldo *et al* (2019, p 134) describe “[how] a specific section of the […] website is dedicated to the uploading of useful documents, guidelines, and newsletters to provide up-to-date public information to various stakeholders” and that technicians and experts are engaged “to provide an overview of climate change and impacts on the urban environment and industrial areas”. Kang *et al* (2017) mention specific investment in R&D for climate change adaptation, however, this was the most rarely used action among their study group.

In contrast to the general adaptation literature which identifies warning and observing systems as one of the most effective adaptation options (Bierbaum *et al* 2013, Biagini *et al* 2014), it does not emerge as a very important option from the literature in our sample. Merely, 16% of papers refer to monitoring/surveillance measures and early warning systems. However, analysing responses to various risk sources, Sakhel (2017, p 111) finds that “physical risks were predominantly tackled by surveillance of physical threats, i.e. monitoring of changes in water supplies, temperature, precipitation, and environmental location factors”.

Adaptation measures to handle risks along the supply chain are mentioned in 16% of papers. Tenggren *et al* (2019) emphasise that both the academic as well as the business communities consider supply chain resilience important and find that all interviewed companies from the Swedish manufacturing industry had supply chain risk management procedures in place. Using data from the Carbon Disclosure Project, Sakhel (2017) finds

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that companies invest in measures to reduce the impacts of physical risks to assets in their own facilities, such as protection devices, as well as through management of supply chain issues, like supply shortages. As supply chains in an increasingly interconnected world tend to become very complex, comprehensive assessments of a firm's vulnerability through potential impacts of a disaster on the supply chains are vital. The main goal in that respect is to maintain the balance between keeping costs down by having only a few suppliers and enlarging the number of suppliers to be less vulnerable whenever disruptions occur (Abe and Ye 2013). Meinel and Abegg (2017) argue that risk prevention and coping capacity can be supported by vertical supply chain integration which, according to Huang *et al* (2014), improves knowledge sharing, trust building and synergies in problem solving.

There is another adaptation option that is rare in the general adaptation literature, yet seems to be specific for the manufacturing industry, which is finance (13% of papers). Finance is crucial in all business areas, but for small and medium enterprises loans, and especially loans after a major disaster, can be vital (Davlasheridze and Geylani 2017). Businesses are also concerned about their ability to repay debt and consider long-term borrowing superior to short-term borrowing in the face of climate change. Other adaptation options aim at increasing financial slack resources, higher cash holding (Huang *et al* 2018), and insurance coverage (Linnenluecke *et al* 2015, Sakhel 2017, Huang *et al* 2018).

As we focus on adaptation to the physical impacts of climate change and not on impacts from regulatory changes, the public sector with its legislative power is a rather insignificant actor within this literature. However, a couple of measures also target policy options to adapt to climate change (16%). These measures span from providing financial incentives to reduce water demand (Chen *et al* 2017), R&D tax credits to invest into new technologies required by climate change adaptation (Jacob et al) to subsidies for environmental investments to e.g., improve the adaptability of companies to high flood risks (Jeßberger *et al* 2010, Linnenluecke *et al* 2015, Ryu *et al* 2017).

The analysis of soft adaptation measures reveals a substantial difference between public and private usage of this type of adaptation. Public adaptation is mostly concerned with early warning systems and providing climate change information (including research) (Bierbaum *et al* 2013), whereas we find that private company adaptation is to a large extent about risk management.

When looking at the relationship between impacts on industry and adaptation measures, we find that soft measures are generally mentioned in combination with impacts on management, such as the change in climate parameters affecting design and planning of long-term projects (Table 2.2.2). On the level of specific measures, risk management and planning in particular is in many cases related to impacts on production processes, such as impacts on stock and production material and impacts on economic performance and costs. In case there is no focus on one specific impact (last column, "not specified"), the majority of the literature refers to soft measures, which

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emphasises the universal applicability of soft adaptation options and underpins their importance as low-barrier and low-regret options to address climate change.

Infrastructure design and adjustment dominate among hard adaptation options

While soft adaptation options are often referred to as no- or low-regret options, as they can produce benefits irrespective of future manifestations of climate change (Watkiss *et al* 2014), hard adaptation options, to the contrary, often require significant investments and long-term decision making (Nakhooda and Watson 2016). Among the hard adaptation measures in our literature sample, infrastructure design andadjustment is the most commonly mentioned option (45% of papers cover such a measure) (see Table A.2 for a detailed list of papers). At least for the adjustment part, this emphasises that incremental changes are preferred over radical changes. Forexample, while relocation is mentioned as a possibility multiple times, it is neverconsidered a viable option, but only discussed as a last resort (Hardisty 2009, Scholten *et al* 2014, Linnenluecke *et al* 2015, Sakhel 2017).

Other hard adaptation options that we have identified in our literature sample aim to render the products' climate-resilience (18%), to improve the infrastructure of utilities (13%) and to adjust transport means and modes (8%). Utility (infrastructure) strategies, for example, include energy and water management practices (Linnenluecke *et al* 2015), "water recycling, reusing water from a tailings dam, and minimization of evaporative water loss" in response to decreases in water allocations (Alkaya *et al* 2015, p 15) or the replacement of soft water-cooled heat transfer pumps with air-cooled pumps in order to reduce soft cooling water consumption in heat transfer systems (Alkaya *et al* 2015). A measure in the transport category entails the reduction of ship size in response to low water levels (Scholten *et al* 2014) or an increase in the number of transport connections or networks to reduce the vulnerability to infrastructure breakdowns (Scholten *et al* 2011).

Hard adaptation options are often mentioned in combination with impacts on stock and production material, production and logistic facilities, impacts on management as well as directly on suppliers (see Table 2.2.2). Again, the most popular choice to address these impacts is a measure from the category infrastructure design and adjustment. Impacts on water supply also often appear in conjunction with hard adaptation options as this involves adaptation of the utility infrastructure.

Ecosystem-based adaptation as accompanying measure

In our literature sample only a few ecosystem-based adaptation measures are mentioned (11% of papers). In each instance, these measures appear jointly with soft adaptation measures and in three out of four cases also together with hard measures. Goldstein *et al* (2019) confirm this finding when analysing the adaptation strategies of 1,630 companies, reported as textual responses to the Carbon Disclosure Project.

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Ecosystem-based adaptation measures appear most frequently in response to impacts on stock and production material, impacts on economic performance and costs and impacts on water supply (Table 2.2.4). Chen *et al.* (2017) study the plastics industry in Taiwan that is prone to water shortage and report several adaptation options to improve water availability, such as rainwater harvesting, waste-water recycling, and on-site desalination plants. In a workshop with a diverse panel of stakeholders from a large integrated chemical manufacturing site in Texas, Reddy *et al* (2015) identify potential solutions to manage water demand and supply: restoration of flood plains and reallocation of reservoir flood pools to storage, restoration or creation of marshes to serve as a regional wastewater treatment facility and land management to replace invasive, high water-use plants with native, low water-use plants to enhance groundwater aquifers and/or stream flows. Also Aguinaldo *et al.* (2019) present a case study for an industrial park in Italy, where a comprehensive adaptation strategy was established; business risks were identified through analysing directly experienced climate events in the common area and collaboration among individual business enterprises, mostly small and medium-sized enterprises, was fostered to share human and financial resources and scientific and technical knowledge to understand climate change risks and response options. One adaptation strategy of the program includes the installation of a flood basin to store, purify and infiltrate rainwater, where the basin will be integrated with the natural landscape and urban green infrastructure (Aguinaldo *et al* 2019).

While the role and importance of ecosystem-based adaptation has been widely discussed (e.g. Munang *et al* 2013) and seems to have been taken up particularly in urban adaptation strategies (Brink *et al* 2016, Geneletti and Zardo 2016), private adaptation strategies still lack green infrastructure planning. A potential reason might be that the benefits of green measures are not clearly accruing to the implementer only but may benefit the broader society and is thus seen as a public good that is expected to be provided by public actors. Additionally, there are many drivers discussed in the literature for why companies engage in corporate social responsibility (Matten 2015) and ecosystem-based adaptation is often aligned with this concept, consequently the general orientation of a company affects the choice of the adaptation approach.

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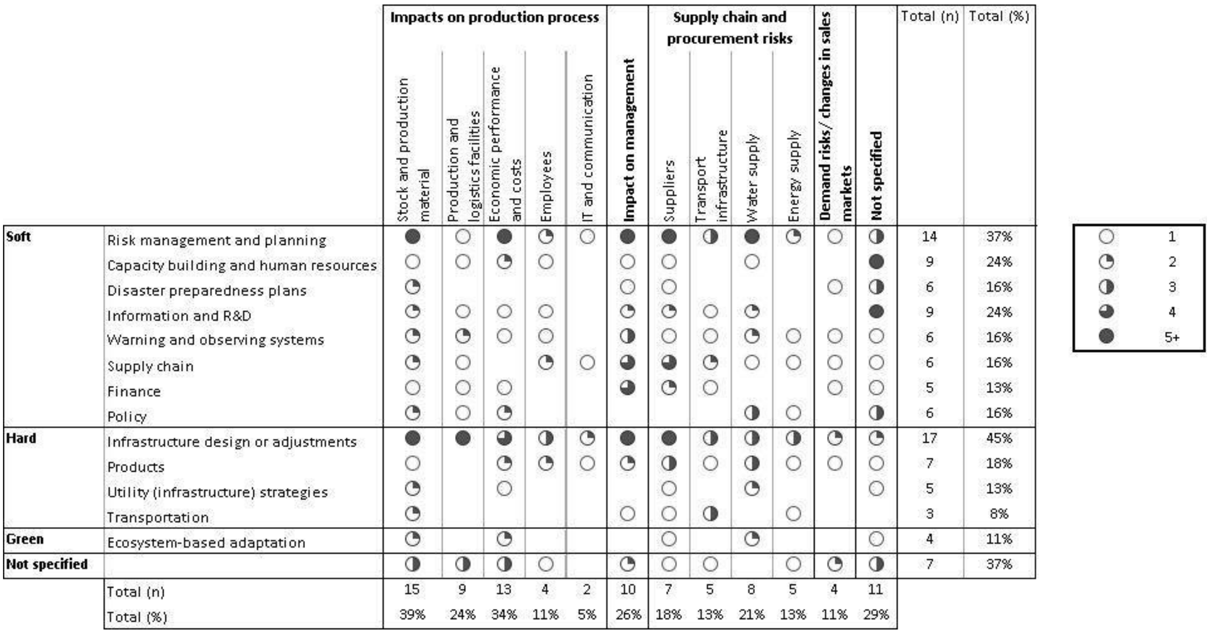

		Impacts on production process					Impact on management	Supply chain and procurement risks				Demand risks/ changes in sales markets	Not specified	Total (n)	Total (%)
		Stock and production material	Production and logistics facilities	Economic performance and costs	Employees	IT and communication		Suppliers	Transport infrastructure	Water supply	Energy supply				
Soft	Risk management and planning	●	○	●	◔	○	●	●	◑	●	◔	○	◑	14	37%
	Capacity building and human resources	○	○	◔	○		○	○		○			●	9	24%
	Disaster preparedness plans	◔					○	○				○	◑	6	16%
	Information and R&D	◔	○	○	○		◔	◔	○	◔			●	9	24%
	Warning and observing systems	◔	◔	○	○		◑	○	○	◔	○	○	○	6	16%
	Supply chain	◔	○		◔	○	◕	◕	◔	○	○	○	○	6	16%
	Finance	○	○	○			◕	◔	○			○	○	5	13%
	Policy	◔	○	◔						◑	○		◑	6	16%
Hard	Infrastructure design or adjustments	●	●	◕	◑	◔	●	●	◑	◑	◑	◔	◔	17	45%
	Products	○		◔	◔	○	◔	◑	○	◑	○	○	○	7	18%
	Utility (infrastructure) strategies	◔		○				○		◔			○	5	13%
	Transportation	◔					○	○	◑		○			3	8%
Green	Ecosystem-based adaptation	◔		◔				○		◔			○	4	11%
Not specified		◑	◑	◑	○		◔	○	○		○	◔	◑	7	37%
	Total (n)	15	9	13	4	2	10	7	5	8	5	4	11		
	Total (%)	39%	24%	34%	11%	5%	26%	18%	13%	21%	13%	11%	29%		

○	1
◔	2
◑	3
◕	4
●	5+

Table 2.2.4: Frequency of papers addressing adaptation actions and potential impacts. Papers addressing multiple adaptation actions or impact categories are only counted once in the total number (*n*) in each category.

Are companies forward-looking?

Finally, we take a look at the timing, goal and motive of the implementation of adaptation measures to find out whether companies are reactive or proactive in their adaptation behaviour. Although the theory provides clear-cut guidance on how to differentiate these two attitudes, in practice many measures are not easily attributed to either of these categories. While reactive climate change adaptation consists in responding to observed climatic changes and the experience of its impacts, proactive adaptation occurs before the impacts arise (Klein 2003).

Although the private sector has been claimed to be insufficiently forward-looking (Goldstein *et al* 2019), we find a prevalence of proactive measures in our literature sample due to several reasons. First, only about half of the reviewed literature refers to extreme weather events (flooding, storms), while the rest deals with gradual climatic changes in temperature and rainfall. Thus, the typical reactive measure after an extreme weather event, such as reconstruction, does not play a crucial role in the sample. Second, as discussed earlier, a large share of measures is soft in type and forward looking in nature and hence proactive. Third, companies tend to implement no- and low-regret options, which are primarily knowledge-based measures and thus again proactive; however, proactivity is no explicit intention (Agrawala *et al* 2011, Averchenkova *et al* 2016). And fourth, it is a matter of the general framing in this literature – as climate change, leading to changes in climatic conditions and an increase in physical risks in the future, is often argued to be the incentive for investing in adaptation, we classify measures as proactive with respect to their motive.

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Drivers and barriers in adapting to heatwaves, supply chain disruptions, and flooding

To give a deeper insight into interlinkages between risks, impacts, adaptation actions and drivers and barriers, we select and discuss three illustrative cases included in our literature sample. The first case covers heatwaves, the second is on supply chain disruptions in the context of extreme events, and the last one deals with flooding.

Heatwaves and heat extremes are among the most relevant risks for industries according to our literature sample (Table 2.2.3). Two major impacts emerge from this risk: impacts on economic performance and costs, and impacts on stock and production material. Table 2.2.3 shows that papers that identify impacts on economic performance and costs also identify risk management and planning as a major adaptation strategy. The study by Lundgren-Kownacki *et al* (2018), for example, supports this finding when analysing occupational heat stress for workers at brick kilns in India. Potential strategies to reduce productivity losses include a switch to alternative brick drying technologies such as using the sun as a natural source of heat or simple behavioural adaptation such as taking rests, drinking water or taking cool showers. In the context of African SMEs, Crick *et al* (2018) find that economic activity in semi-arid zones can be impaired by an increase in the number of hot days. A potential adaptation option is finance, however, the availability and cost of finance is also reported as the most important barrier to action. The impact on stock and production material through the physical risk heat is more often addressed through infrastructure design or adjustments. However, in order to enable changes in infrastructure design, firms need access to finance and can also benefit from technical assistance (Lundgren-Kownacki *et al* 2018).

We find that supply chain disruptions due to extreme events, such as storms, hurricanes, flooding or heatwaves, are an often stated risk. Although several adaptation measures are available, like infrastructure design or adjustment and risk management and planning as well as supply chain management and warning and observing systems, firms are often limited in their financial capability and in their choice of potential suppliers, with a reliance on inputs from climate change exposed countries. Abe and Ye (2013) offer a good discussion on adaptation to supply chain shocks based on the flooding in Thailand in 2011, which affected large parts of the local industry, in particular SMEs, as they were concentrated in one location to minimize costs. Due to Thailand's upstream position in the global supply chain, the economic impact of the flood propagated globally, e.g. it affected the Japanese car manufacturing, which was reliant on numerous car component suppliers in Thailand. A potential adaptation option is supply chain management, which actively takes the risk exposure of the individual supplier into account, diversifies the risk by using different distribution channels and suppliers, and increases the supply chain transparency through the use of monitoring systems. A potential driver would be to strengthen public-private partnerships to implement insurance schemes, which compensate for disaster damage. This is particularly important for SMEs and creates incentives for companies to engage in adaptation measures. Public-private partnerships could also serve as a means to exchange information on disaster risk and individual and joint risk-reduction measures.

Flooding is often associated with impacts on stock and production material but also with impacts on management (Table 2.2.3). Impacts on stock and production material are primarily addressed through risk management and planning and infrastructure design and adjustment. The impacts on management mainly require soft measures, such as supply chain management, finance or warning and observing systems and again risk management and planning. Hardisty (2009) emphasizes the importance of planning by means of a new petrochemical plant with a design life of 50 years that is supposed to be built in a future flood prone area. As yet, no flooding has occurred, however, climate projections indicate that the respective area with an average elevation of 0.4 m above sea level is likely to be flooded or exposed to increased storm surges. With a focus on the Korean industry, Kang *et al* (2017) analyse factors that drive climate action and find that half of their sample have already experienced flooding, and more than half of the sample expects to experience flooding in the future. Potential adaptation options in this context are again disaster preparedness plans and other risk management measures. Identifying flooding as a major risk to industry, Sakhel (2017) reports that the development of plans for crisis management and business continuity at an operational level is key for dealing with flood risk. In particular, business continuity plans are designed to minimise losses to the company following an interruption in operation by ensuring a rapid resumption of business (Sakhel 2017). On a local scale, knowledge exchange networks can act as a driver to adaptation in supporting companies in their risk management and planning. On a bigger scale, however, adaptation to floods often requires large structural investments, with insufficient financial means constituting a distinct barrier to adaptation. This calls for government support, as in many cases the individual realisation is not feasible for a single company. Ryu *et al* (2017), for example, investigate how the government can support companies in reducing overall flood damages providing a reference for decision-making in allocating taxes and infrastructure building in high-risk industrial parks in the country.

Conclusion

According to this systematic literature review, the most prevalent physical risks for companies in the manufacturing industry are storm, heat, drought and water shortage, and coastal and riverine flooding. These risks translate into damages to production stocks and assets, lead to reduced economic performance and higher costs, and also affect management, e.g., a change in investment decisions due to reduced capital, or a lower market valuation.

Risk management and planning is the most frequently mentioned adaptation measure and seems to address not only management risks but also an array of other risks, such as damage to stock and material, economic performance, and supply chain and procurement risks. Infrastructure design or adjustment, as the most frequently stated hard adaptation option, may reduce not only damages to assets but also damages to stock and material, as well as deal with management and supply and procurement risks. Adaptation measures that can be taken at the company level, such as risk management (36%), capacity building (24%), and information and R&D (24%), are mentioned more

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frequently than public adaptation measures, such as policies supporting or mandating adaptation (16%), and warning and observation systems (16%).

We find a prevalence of proactive measures in our literature sample. The prevalence of soft adaptation options (information provision etc.) as well as the companies' tendency to implement no- and low-regret options contribute to this finding. Moreover, companies seem to predominantly identify risks to direct operations, while risks to supply chains seem to be underestimated and therefore not sufficiently addressed by adaptation actions. Only one paper suggests to include price hedging provisions in contracts to protect against price volatility (Sakhel 2017).

While papers assessing the impacts on the manufacturing industry in detail frequently mention risks of temporary business interruption or a permanent inability to do business, papers focusing on adaptation actions mostly discuss incremental adaptation options that present low-regret options such as many soft adaptation options and in particular risk management and planning. Transformational adaptation (Kates *et al* 2012, Pelling *et al* 2015) that would require a more fundamental change in how and where the company operates, is rarely discussed: Relocation is mentioned as a possibility multiple times, but it is not considered a viable option, and only discussed as a last resort (Hardisty 2009, Scholten *et al* 2014, Linnenluecke *et al* 2015, Sakhel 2017). Potential other examples of transformational adaptation for the manufacturing industry are a fundamental change in the manufacturing process, e.g., to accommodate for more frequent water shortages (e.g., replacing the cooling technology in the chemical industry), or a change in the product. Neise *et al* (2018) give an example for medium-sized and large-scale enterprises in Jakarta that introduced novel emergency response teams after the floods in 2007 and 2012, which indicates a radical shift in strategies to manage risks.

Insufficient or no adaptation is discussed in some of the papers in the sample (e.g., Kang *et al* 2017, Meinel and Höferl 2017), but maladaptation is not addressed explicitly. Maladaptation refers to adaptation actions that increase greenhouse gas emissions, have high opportunity costs, or create path dependencies (Barnett and O'Neill 2010, UN Global Compact *et al* 2015). For companies in the manufacturing industry, maladaptation could arise when increased demand for cooling water adversely affects communal water supply (UN Global Compact *et al* 2015), or path dependencies generated by large scale infrastructure such as structural flood protection, that in addition may attract companies to locate in flood prone areas in a false perception of safety.

Several gaps remain for further research. First, more research is needed on the effectiveness of corporate adaptation actions, in particular for adaptation to external risks of companies such as supply chain risks, and on coordination across companies and with the public sector. Second, the topic of transformational adaptation for the manufacturing industry necessitates further investigation. Finally, maladaptation is also under-researched in the context of the manufacturing industry. Given the scale of the manufacturing industry in industrialized economies, better knowledge on potential trade-offs, e.g. of increased water and energy use for other systems and groups of society, seems fundamental.

2.2.2. Consequences of supply chain interruptions for European industries and implications for adaptation

Introduction

Climate change and urbanization are increasing the scale, frequency and destructiveness of natural hazards in many areas of the world. According to a 2020 survey of experts by the World Economic Forum, extreme weather events are the mostcritical of all global threats faced by economies today because of their high likelihood ofoccurrence and significant potential impacts.[1]

Globalization of production networks means that disasters have impacts far from where they directly hit. Localized damage to facilities and infrastructure can slow or shut down local production, causing input scarcity, price distortions, and declines in output and revenue for non-local firms connected through the supply chain (Carvalho 2014). For example, the 2011 Earthquake in Eastern Japan led to a drop in automobile production of 24 percent in the Philippines, 19.7 percent in Thailand and 6.1 percent in Indonesia (Ye & Abe 2012).

A burgeoning strand of literature gives evidence that particular trade network characteristics can dampen or amplify natural disaster shocks that ripple through supply chains. Evidence primarily from theoretical models and case studies shows that having a large number of input suppliers serves as a layer of protection as it enables firms to more easily find substitutes for damaged suppliers (Henriet, Hallegate & Tabourier 2012). Input supplier concentration, on the other hand, creates production bottlenecks as firms have no or few alternatives to make up for their lost input supply. In their analysis of U.S. disasters, Barrot & Sauvagnat (2016) determined input supplier concentration to be a key driver in the propagation of disaster shocks through supply chains: firms' performance indicators significantly suffered only when a major disaster hit an input supplier for which they had few to zero substitutes. The same is true for firms indirectly affected by the Tōhoku Earthquake: firms with many input suppliers located outside the disaster-stricken area experienced shortened recovery times. Evidence from Hurricane Sandy yields similar conclusions: firms with international, diversified supply chains were not negatively affected by the hurricane because they more easily substituted away from damaged input suppliers. In short, while firms with many connections are more exposed to non-local disaster shocks, they are also more resilient.

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[1] https://www.weforum.org/reports/the-global-risks-report-2020

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This work package expands on previous literature by empirically testing the hypothesis that diversified trade networks dampen extreme weather shocks that propagate through supply chains. We identify the effect of diversified trade networks with an extensive measure and an intensive measure of input supplier concentration. The two measures capture the extent to which importers diversify their input supply chain. Following previous literature, we postulate that a more concentrated input supply chain will also have higher “switching costs” associated with extreme weather shocks to upstream input suppliers, ultimately leading to a degradation in downstream export performance.

This study contributes to several strands of literature. It relates to a growing body of work assessing the mediating effect of input supplier diversification in supply chain shock propagation. With theoretical frameworks and simulations, Henriet et al. (2012) and Shughrue, Werner, & Seto (2020) offer illustrative evidence that redundancy in input suppliers acts as a risk-sharing mechanism against disaster shocks, improving overall economic robustness. Several empirical analyses have addressed the same topic, focusing primarily on how specific disasters like the Tōhoku Earthquake and Hurricane Sandy propagated through supply chains (Boehm, Flaaen, & Pandalai-Nayar 2019; Carvalho, Nirei, Saito, and Tahbaz-Salehi 2021; Todo, Kashiwagi, & Matous 2021), or within-country analyses of multiple disasters over time (Barrot & Sauvagnat 2016).
In contrast to other empirical works, this paper's setting encompasses twenty years of extreme weather events and trade linkages between 170 countries, thereby generating a more complete picture of how input supplier concentration relates to the propagation of extreme weather shocks through international supply chains. In particular, our results demonstrate that a diversified supply chain provides resiliency for the average country against the average extreme weather shock, and that the benefits of a diversified supply chain are not limited to large disasters like the Tōhoku Earthquake nor especially wealthy countries like the United States and Japan.

This study builds on the work package D.2.4., which finds that supply chain disruptions caused by large natural disasters abroad significantly reduces a sector's export value. This work package explores the role of input supplier concentration in mediating the adverse effects of supply chain disruptions. To do so, two measures of input supplier concentration are constructed, which are based on an extensive multi-region input-output dataset. These measures are then used in the econometric framework determined in work package D.2.4. Based on this empirical strategy, we describe differences in input supplier concentration between countries and industries and provide econometric evidence on how these differences affect the strength of supply chain disruptions.

Empirical Strategy and Data

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The empirical strategy builds on the econometric model as laid out in work-package D.2.4. To investigate the relationship between extreme weather shock propagation over supply chain networks and input supplier concentration, we estimate the following model:

$$Y_{\mathrm{kit}} \quad \beta \ + \beta \ Shock_{\mathrm{kit}} + \beta \ Concentration_{\mathrm{kit}} \ \ + \beta \ Shock_{\mathrm{kit}} * Concentration_{\mathrm{kit}} \qquad 1$$
$$+ \beta_4 X_{\mathrm{kit}} + \lambda_{\mathrm{kt}} + \theta_{\mathrm{ki}} + \zeta_{\mathrm{it}} + \varepsilon_{\mathrm{kit}}$$

The unit of measurement is an industry-country-year observation. The dependent variable, Y_{kit}, measures the logged export value of industry k, in country i in year t. Information about export flows comes from the World Integrated Trade Solutions (WITS) database, which itself is based on the UN's commodity trade statistic database.[2]

$Shock_{\mathrm{kit}}$, is a measure of extreme weather shock transmission over the supply chain to industry k, in country i in year t. The variable is an index that combines a variable indicating if an upstream, input supplier was recently directly hit by either a heatwave, cold wave, drought, spring flood or riverine flood, with information about the degree of supply chain connectivity between the upstream-downstream trading partners. $Shock_{\mathrm{kit}}$ is equal to zero if the country of an input supplier was not directly hit by an extreme weather event in year t and/or there is no supply chain connectivity between the two trading partners. The variable is greater than zero if an input supplier's country was directly hit by an extreme weather event and there is supply chain connectivity between the two trading partners. The size of the variable increases with the level of connectivity. If upstream extreme weather shocks reduce downstream firms' average productivity, the coefficient β will be negatively signed. Information about supply chain connectivity comes from the EORA global supply chain database, a multi-region input-output table that is based on the supply-use tables from the full EORA multi-regional input-output tables. They have been converted to symmetric product-by-product input-output tables using the industry technology assumption and aggregated to a common 26-sector classification.[3] Extreme weather event information is derived from daily 2-meter air temperature, and precipitation rate readings on a 0.5°x0.5° regular latitude-longitude grid collapsed on year-country pairs.

$Concentration_{\mathrm{kit}}$ is the measure of input supplier concentration for country i, industry k in year $t - \ 1$. For a broad view of the impact of diversified trade networks, we construct two different measures of input supplier concentration. The first measure is the extensive margin of input supplier concentration. It is calculated by summing the number of countries supplying a given country-industry pair, and dividing that sum by the number of industries supplying that same country-industry pair. A higher value of the extensive margin indicates a more diversified supply chain. The second measure

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[2] http://wits.worldbank.org/wits/

[3] Please see Lenzen, Kanemoto, Moran & Geschke (2012), Lenzen, Moran, Kanemoto & Geschke (2013) and https://worldmrio.com/eora26/ for a more detailed description.

captures the importance of each supplier in relation to total input supply with the Herfindahl-Hirschman-Index. We term this second measure the intensive margin of input supplier concentration. A higher intensive margin of input supplier concentration indicates a large share of input supply originating from few suppliers, i.e. a less diversified supply chain. We lag supplier concentration by one year due to simultaneity between the number of suppliers and the export value of an industry. Information about input supplier concentration also comes from the intermediate good sales matrix in EORA's multi-regional input-output tables.

Our main variable of interest, $Shock_{\mathrm{kit}} * Concentration_{\mathrm{kit}}$, is the interaction of the shock transmission variable and the input supplier concentration variable. The variable measures the mediating effect input supplier concentration may have on shock propagation over supply chains. We postulate that industries with a large number of equally important input suppliers are more resilient to extreme weather shocks that propagate over supply chains compared to industries with a high concentration of input suppliers. This is because industries with low input supplier concentration have multiple options to reroute and/or substitute input, thus reducing "switching costs", in the case that a particular input supplier's production is disrupted.

λ_{kt}, is a year dummy, covering all characteristics that vary over industries within a specific year and influence the export activity of an industry, e.g., industry-specific business cycles. θ_{ki}, is a country-industry dummy, and accounts for all time-invariant industry-specific characteristics within a country, e.g., the capital intensity of specific industries within a country, which can make them relatively inelastic to adapt to short-term demand changes, or the degree of returns to scale. ζ_{it}, is a country-year dummy, which captures all country-specific factors that change over time and affect an industry's export performance, e.g., the occurrence of a domestic disaster or the financial crisis in the year 2008. X_{kit}, is a vector of industry characteristics in country i, which affect an industry's export intensity and vary over time, e.g., the economic size of an industry or the degree of foreign competition. Finally, the error term, $\varepsilon_{\mathrm{kit}}$, is assumed to be i.i.d. and clustered over country and industry.

With our fixed effect structure, we aim to disentangle the role of input supplier concentration in mediating the impact of an exogenous short-term supply chain shock on the exporters' productivity and the resulting export decision from other confounding factors. Our identification of an exogenous short-term supply chain shock comes by comparing the export performance of different industries, which are differently exposed to supply chain shocks and exhibit different levels of input supplier concentration in the same country, with the export performance of the same industry in other countries.

We perform our analyses on a sample amounting to 32,001 observations, spanning 170 countries and 12 industries, from 1995 to 2015. The database contains input-output connections for countries across all five world regions (the Americas, Asia, Africa,Europe, and Oceania) and comprises the vast majority of global trade in this time period.

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Results: Input supplier concentration affects shock transmission

Table 2.2.5 presents the study's main results. In Column (1) and (2) the relationship between extreme weather shock propagation over supply chain networks and the *extensive* margin of input supplier concentration is analyzed. Column (3) and (4) depict the results for the *intensive* margin of input supplier concentration in that context. Columns (1) and (3) contain baseline estimates for the propagation of extreme weather event shocks over supply chain networks. As indicated by the negative and significant coefficients on the $Shock$ variable, supply chain shocks from upstream input suppliers significantly reduce downstream trading partners' export performance. From Column (1), we also find that country-industry pairs with a larger extensive measure of input supplier concentration also have a higher export value, though the relationship is not statistically significant. From Column (3), we see that country-industry pairs with a larger intensive measure of supplier concentration have a statistically significant lower export value. Regarding the country-industry specific control variables, larger industries, measured by the gross output in year t, tend to export more, though the relationship is not statistically significant. An increase in foreign competition, after controlling for country-industry, country-year, and industry-specific fixed effects, does not show an economic and statistically significant impact on an industry's export performance.

Table 2.2.5: Estimation results - Supply chain shocks, supplier concentration and a country's exports

	(1)	**(2)**	**(3)**	**(4)**
Shock	-0.339**	-0.108	-0.336**	0.331
	(0.154)	(0.174)	(0.153)	(0.295)
Concentration	0.022	0.005	-0.581*	-0.408
	(0.024)	(0.025)	(0.346)	(0.339)
Shock * Concentration		0.041***		-0.438***
		(0.015)		(0.180)
Competition	-0.007	0.010	0.000	0.002
	(0.661)	(0.656)	(0.659)	(0.655)
(ln) Goutput	0.059	0.059	0.087	0.086
	(0.127)	(0.127)	(0.127)	(0.127)
Country-year FX	Yes	Yes	Yes	Yes
Country-industry FX	Yes	Yes	Yes	Yes
Year-industry FX	Yes	Yes	Yes	Yes
Observations	32,001	32,001	32,001	32,001
adj. R^2	0.940	0.940	0.940	0.940

Notes: Dep. Variable: (ln) export. In column (1) a baseline model with number of suppliers is shown. Column (2) depicts the results for interacting the number of suppliers and supply chain shocks. Column (3) shows the results of the baseline model with concentration in the supplier market. Column (4) depicts the results for the interaction of supplier market concentration and supply chain shocks. *, **, *** indicate 10, 5, 1 % significance levels. Standard errors clustered at the county-industry level. Constant included but not reported.

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Columns (2) and (4) depict the results of the full model as specified in Equation 1, which accounts for the mediating role of input supplier concentration on the impact of supply chain shock. Our results demonstrate that supply chain shock propagation is affected by the extent to which a country-industry has diversified its supply chain. As evidenced by the statistically significant coefficients on the $Shock * Concentration$ variable in the two columns, the negative shock from the extreme weather event is counteracted with increasing supplier choice. Please note that the direction of the interaction terms differs as a higher number in the extensive margin, i.e., a higher number of input suppliers, and a lower number in the intensive margin, i.e., a less concentrated supply chain, depict a lower level of input supplier concentration.

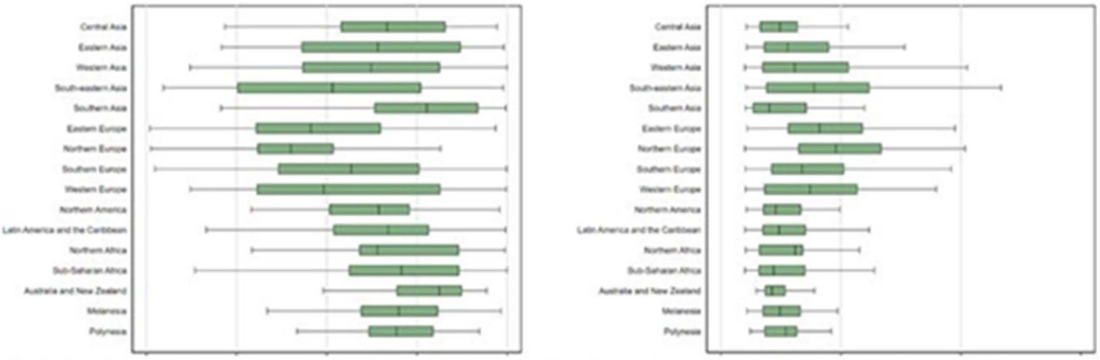

Figure 2.2.5: Geographical distribution of supplier concentration. Left panel depicts the extensive margin of supplier concentration. Right panel the intensive margin.

Figure 2.2.5 gives insights into the geographical distribution of the extensive and intensive measures of input supplier concentration. Due to their geographical centrality and their role in global production networks, countries in Southeast Asia and countries situated in Europe tend to be more strongly integrated into the supply chain network compared to countries in Africa, South America and North America. From the results of Equation 1, that means, all else equal, countries in Africa, South America and North America will also be more exposed to export performance degradation in case of a supply chain shock.

Tables 2.2.6 and 2.2.7 present the same information for European Union countries and the United Kingdom specifically, though broken down by industry. In both tables, red represents greater input supplier concentration and green lesser input supplier concentration. Across the continent, agriculture, fishing, mining and quarrying and electricity, gas and water are the industries with the least diversified supply chain, and consequently most exposure to shock propagation due to large switching costs.

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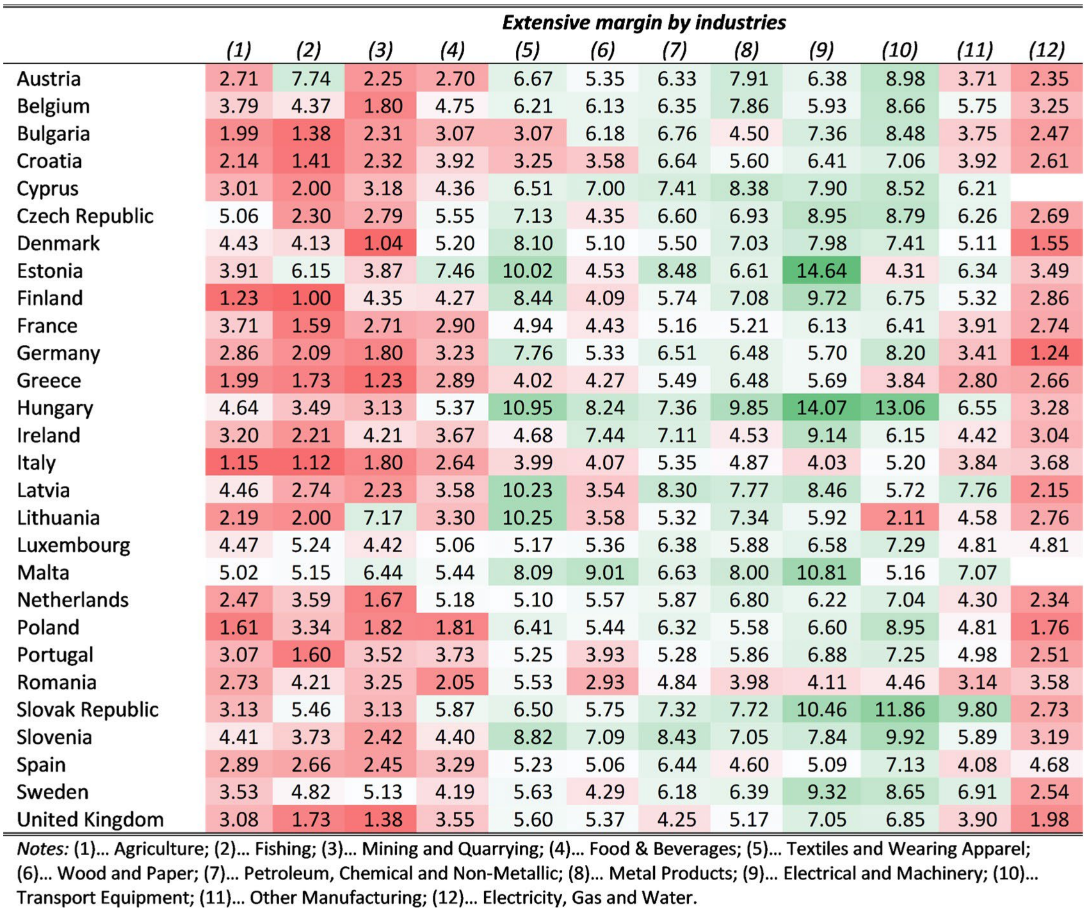
Romania, Bulgaria and Italy are the countries with the most highly concentrated input supply chains.

Table 2.2.6: Extensive margin of input supplier concentration by Industries for selected countries



	Extensive margin by industries											
	(1)	*(2)*	*(3)*	*(4)*	*(5)*	*(6)*	*(7)*	*(8)*	*(9)*	*(10)*	*(11)*	*(12)*
Austria	2.71	7.74	2.25	2.70	6.67	5.35	6.33	7.91	6.38	8.98	3.71	2.35
Belgium	3.79	4.37	1.80	4.75	6.21	6.13	6.35	7.86	5.93	8.66	5.75	3.25
Bulgaria	1.99	1.38	2.31	3.07	3.07	6.18	6.76	4.50	7.36	8.48	3.75	2.47
Croatia	2.14	1.41	2.32	3.92	3.25	3.58	6.64	5.60	6.41	7.06	3.92	2.61
Cyprus	3.01	2.00	3.18	4.36	6.51	7.00	7.41	8.38	7.90	8.52	6.21	
Czech Republic	5.06	2.30	2.79	5.55	7.13	4.35	6.60	6.93	8.95	8.79	6.26	2.69
Denmark	4.43	4.13	1.04	5.20	8.10	5.10	5.50	7.03	7.98	7.41	5.11	1.55
Estonia	3.91	6.15	3.87	7.46	10.02	4.53	8.48	6.61	14.64	4.31	6.34	3.49
Finland	1.23	1.00	4.35	4.27	8.44	4.09	5.74	7.08	9.72	6.75	5.32	2.86
France	3.71	1.59	2.71	2.90	4.94	4.43	5.16	5.21	6.13	6.41	3.91	2.74
Germany	2.86	2.09	1.80	3.23	7.76	5.33	6.51	6.48	5.70	8.20	3.41	1.24
Greece	1.99	1.73	1.23	2.89	4.02	4.27	5.49	6.48	5.69	3.84	2.80	2.66
Hungary	4.64	3.49	3.13	5.37	10.95	8.24	7.36	9.85	14.07	13.06	6.55	3.28
Ireland	3.20	2.21	4.21	3.67	4.68	7.44	7.11	4.53	9.14	6.15	4.42	3.04
Italy	1.15	1.12	1.80	2.64	3.99	4.07	5.35	4.87	4.03	5.20	3.84	3.68
Latvia	4.46	2.74	2.23	3.58	10.23	3.54	8.30	7.77	8.46	5.72	7.76	2.15
Lithuania	2.19	2.00	7.17	3.30	10.25	3.58	5.32	7.34	5.92	2.11	4.58	2.76
Luxembourg	4.47	5.24	4.42	5.06	5.17	5.36	6.38	5.88	6.58	7.29	4.81	4.81
Malta	5.02	5.15	6.44	5.44	8.09	9.01	6.63	8.00	10.81	5.16	7.07	
Netherlands	2.47	3.59	1.67	5.18	5.10	5.57	5.87	6.80	6.22	7.04	4.30	2.34
Poland	1.61	3.34	1.82	1.81	6.41	5.44	6.32	5.58	6.60	8.95	4.81	1.76
Portugal	3.07	1.60	3.52	3.73	5.25	3.93	5.28	5.86	6.88	7.25	4.98	2.51
Romania	2.73	4.21	3.25	2.05	5.53	2.93	4.84	3.98	4.11	4.46	3.14	3.58
Slovak Republic	3.13	5.46	3.13	5.87	6.50	5.75	7.32	7.72	10.46	11.86	9.80	2.73
Slovenia	4.41	3.73	2.42	4.40	8.82	7.09	8.43	7.05	7.84	9.92	5.89	3.19
Spain	2.89	2.66	2.45	3.29	5.23	5.06	6.44	4.60	5.09	7.13	4.08	4.68
Sweden	3.53	4.82	5.13	4.19	5.63	4.29	6.18	6.39	9.32	8.65	6.91	2.54
United Kingdom	3.08	1.73	1.38	3.55	5.60	5.37	4.25	5.17	7.05	6.85	3.90	1.98

Notes: (1)… Agriculture; (2)… Fishing; (3)… Mining and Quarrying; (4)… Food & Beverages; (5)… Textiles and Wearing Apparel; (6)… Wood and Paper; (7)… Petroleum, Chemical and Non-Metallic; (8)… Metal Products; (9)… Electrical and Machinery; (10)… Transport Equipment; (11)… Other Manufacturing; (12)… Electricity, Gas and Water.

Table 2.2.7: Intensive margin of input supplier concentration by Industries for selected countries

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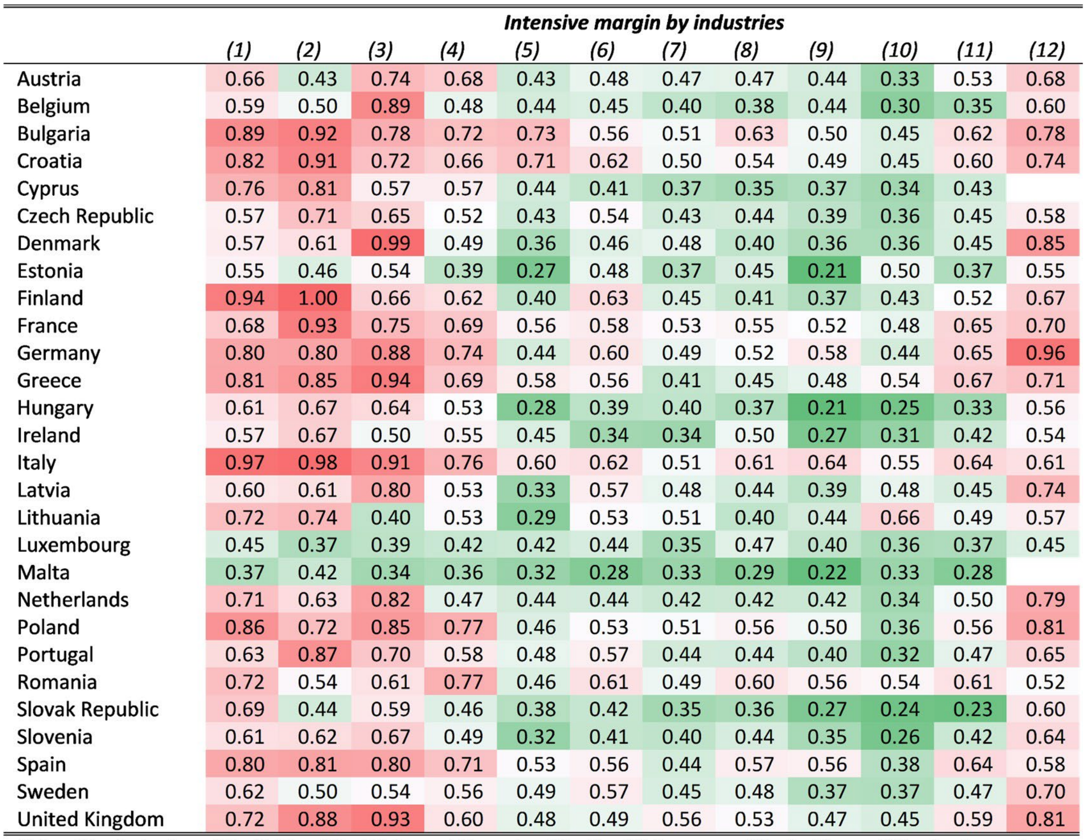

	Intensive margin by industries											
	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)	(10)	(11)	(12)
Austria	0.66	0.43	0.74	0.68	0.43	0.48	0.47	0.47	0.44	0.33	0.53	0.68
Belgium	0.59	0.50	0.89	0.48	0.44	0.45	0.40	0.38	0.44	0.30	0.35	0.60
Bulgaria	0.89	0.92	0.78	0.72	0.73	0.56	0.51	0.63	0.50	0.45	0.62	0.78
Croatia	0.82	0.91	0.72	0.66	0.71	0.62	0.50	0.54	0.49	0.45	0.60	0.74
Cyprus	0.76	0.81	0.57	0.57	0.44	0.41	0.37	0.35	0.37	0.34	0.43	
Czech Republic	0.57	0.71	0.65	0.52	0.43	0.54	0.43	0.44	0.39	0.36	0.45	0.58
Denmark	0.57	0.61	0.99	0.49	0.36	0.46	0.48	0.40	0.36	0.36	0.45	0.85
Estonia	0.55	0.46	0.54	0.39	0.27	0.48	0.37	0.45	0.21	0.50	0.37	0.55
Finland	0.94	1.00	0.66	0.62	0.40	0.63	0.45	0.41	0.37	0.43	0.52	0.67
France	0.68	0.93	0.75	0.69	0.56	0.58	0.53	0.55	0.52	0.48	0.65	0.70
Germany	0.80	0.80	0.88	0.74	0.44	0.60	0.49	0.52	0.58	0.44	0.65	0.96
Greece	0.81	0.85	0.94	0.69	0.58	0.56	0.41	0.45	0.48	0.54	0.67	0.71
Hungary	0.61	0.67	0.64	0.53	0.28	0.39	0.40	0.37	0.21	0.25	0.33	0.56
Ireland	0.57	0.67	0.50	0.55	0.45	0.34	0.34	0.50	0.27	0.31	0.42	0.54
Italy	0.97	0.98	0.91	0.76	0.60	0.62	0.51	0.61	0.64	0.55	0.64	0.61
Latvia	0.60	0.61	0.80	0.53	0.33	0.57	0.48	0.44	0.39	0.48	0.45	0.74
Lithuania	0.72	0.74	0.40	0.53	0.29	0.53	0.51	0.40	0.44	0.66	0.49	0.57
Luxembourg	0.45	0.37	0.39	0.42	0.42	0.44	0.35	0.47	0.40	0.36	0.37	0.45
Malta	0.37	0.42	0.34	0.36	0.32	0.28	0.33	0.29	0.22	0.33	0.28	
Netherlands	0.71	0.63	0.82	0.47	0.44	0.44	0.42	0.42	0.42	0.34	0.50	0.79
Poland	0.86	0.72	0.85	0.77	0.46	0.53	0.51	0.56	0.50	0.36	0.56	0.81
Portugal	0.63	0.87	0.70	0.58	0.48	0.57	0.44	0.44	0.40	0.32	0.47	0.65
Romania	0.72	0.54	0.61	0.77	0.46	0.61	0.49	0.60	0.56	0.54	0.61	0.52
Slovak Republic	0.69	0.44	0.59	0.46	0.38	0.42	0.35	0.36	0.27	0.24	0.23	0.60
Slovenia	0.61	0.62	0.67	0.49	0.32	0.41	0.40	0.44	0.35	0.26	0.42	0.64
Spain	0.80	0.81	0.80	0.71	0.53	0.56	0.44	0.57	0.56	0.38	0.64	0.58
Sweden	0.62	0.50	0.54	0.56	0.49	0.57	0.45	0.48	0.37	0.37	0.47	0.70
United Kingdom	0.72	0.88	0.93	0.60	0.48	0.49	0.56	0.53	0.47	0.45	0.59	0.81

Notes: (1)… Agriculture; (2)… Fishing; (3)… Mining and Quarrying; (4)… Food & Beverages; (5)… Textiles and Wearing Apparel; (6)… Wood and Paper; (7)… Petroleum, Chemical and Non-Metallic; (8)… Metal Products; (9)… Electrical and Machinery; (10)… Transport Equipment; (11)… Other Manufacturing; (12)… Electricity, Gas and Water.

In an extension, as depicted in Table 2.2.8, we explore differences in the economic importance of suppliers within the supply chain network. We introduce two different thresholds, representing the strength of interconnection between two sectors in the supply chain network. The strength of interconnection between two sectors is given by the Leontief Inverse of the intermediate goods sales matrix in the EORA's 26 sector multi-regional input-output tables. Each element of the Leontief inverse summarizes all direct and indirect effects created in one sector to supply a single unit of final demand for another sector. The stricter threshold, which focuses purely on an input supply network of large exporter countries, only considers sectors where a one-unit increase in final demand in another sector increases the production by at least 0.1 units. This threshold reduces the network to 7,983 annual input flows on average, which are above this threshold. The less strict threshold, which also considers smaller intermediate goods trade flows, sets a cutoff by 0.01 units to be considered in the network, which results in 81,795 annual input flows on average. For both measures we see that the size of the relevant substitute suppliers plays a role in the mediating effect of input supplier: in case of a supply chain shock, it is far more important to have multiple large input suppliers that can substitute for missing input, than many suppliers of all sizes.

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Table 2.2.8: Differences in the economic relevance of suppliers within the supply chain network

	Extensive margin		**Intensive Margin**	
	0.1	***0.01***	***0.1***	***0.01***
	(1)	**(2)**	**(3)**	**(4)**
Shock	-0.220	-0.173	0.510	-0.014
	(0.176)	(0.159)	(0.308)	(0.261)
Concentration	0.052*	0.006	-0.394	-0.118
	(0.032)	(0.016)	(0.308)	(0.500)
Shock * Concentration	0.046**	0.019***	-0.576***	-0.316
	(0.023)	(0.007)	(0.178)	(0.208)
Other controls	Yes	Yes	Yes	Yes
Country-year FX	Yes	Yes	Yes	Yes
Country-industry FX	Yes	Yes	Yes	Yes
Year-industry FX	Yes	Yes	Yes	Yes
Observations	31,951	32,027	31,968	32,027
adj. R^2	0.941	0.940	0.941	0.940

Notes: Dep. Variable: (ln) export. Column (1) and (3) depict the results based on a network of input supply with a 0.1 percent threshold. Column (2) and (4) depict the results based on a network of input supply with a less strict 0.01 percent threshold. *, **, *** indicate 10, 5, 1 % significance levels. Standard errors clustered at the county-industry level. Constant included but not reported.

Conclusion

Our findings highlight the importance of supply chain resiliency in the face of growing natural hazard risk. Increasingly globalized and efficient production networks over the past few decades have simultaneously led to economic growth and increased exposure to disaster shocks. As extreme weather events increasingly exceed the design thresholds of current production facilities and infrastructure, the trade-off between supply chain efficiency that comes from a limited number of input suppliers and resiliency that comes from a large number of input suppliers is expected to become even more apparent.

This paper provides empirical evidence that having a diversified supply chain contributes to resiliency against non-local extreme weather shocks. Keeping this insight in mind, we find large geographical and sectoral differences in the degree of input supplier concentration. Due to their geographical centrality and their role in global production networks, countries in Southeast Asia and countries situated in Europe tend to have less concentrated input supply chains than countries in Africa, South America, and North America. Within Europe, industries and countries strongly differ in the level of supply chain diversification. We find that agriculture, fishing, mining and quarrying, and electricity, gas and water are the industries with the least diversified supply chain, and consequently, most exposure to shock propagation due to high switching costs. Romania, Bulgaria, and Italy are the countries with the most highly concentrated input supply chains. Finally, the size of the relevant substitute suppliers plays a role in the mediating effect of input suppliers: in case of a supply chain shock, it is far more

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important to have multiple large input suppliers that can substitute for missing input than many suppliers of all sizes.

Firms may use this information to make decisions surrounding the amount of efficiency in normal times they are willing to forfeit for supply chain robustness in case of disaster. Governments and other aid organizations may use this information in designing policies and investments that promote supply chain diversity as well as planning for extreme weather shocks that propagate along the supply chain.

2.2.3 An assessment of adaptation pathways for European seaports and supply chain networks

Introduction

Roughly 90% of global trade passes through seaports, meaning that they play an invaluable, and to many – invisible, role in modern society (Becker et al., 2012). As such, they are critical hubs in global, national, and local supply chains (Becker et al., 2018). The associated hinterland transport networks (including roads, rails, waterways, and terminals), are equally vital to ensuring the efficient and reliable movement of goods along the supply chain (UNECE, 2021). The resilience of this infrastructure in the face of climate change is thus of critical importance.

With this consideration in mind, the following case study explores the research question: *Which sets of adaptation measures can increase climate resilience of intermodal transport hubs, particularly for ports and the associated supply chain networks?*

The aim of this case study is to present a *robust* approach to assessing climate impacts and identifying adaptation options and strategies for ports, the hinterland transport network, and the broader supply chain. To this end, we have used a modified adaptation pathways approach, presenting a range of adaptation responses for different scenarios. The pathways approach is particularly suitable as a robust methodology, as it identifies adaptation strategies that perform across a range of possible future climate scenarios.

To frame the study, the North Sea Region serves as the basis of the research, due to its position as the most important logistical hub in Europe (Interreg, 2014). This includes major ports like those in Rotterdam and Hamburg, key inland waterways such as the Rhine River and its tributaries, and important elements of the Trans-European Transport Network (TEN-T). In sum, these diverse elements will face a broad range of climate impacts and vulnerabilities, making resilient adaptation a key priority for planning and policymaking.

Methodology

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Our approach to the study is rooted in *robust decision making*, a decision making framework that is particularly helpful in dealing with large uncertainties, and which can assess the performance of adaptation strategies across a range of different possible future climate scenarios (Tröltzsch et al., 2016). Specifically, the methodology we have employed for the case study builds on an adaptation pathways approach (Haasnoot et al., 2012), and proposes the use of participatory processes (i.e. workshops or survey) to elicit basic qualitative information from stakeholders. This approach is well suited for preliminary, rough assessments of adaptation pathways in the context of adaptation management for ports, supply chains, and transport networks, particularly where quantitative information may be limited.

The adaptation pathways approach was developed by Haasnoot et al. (2012) as a means of supporting decision making through the identification of: opportunities, threats, and the timing and sequencing of adaptation measures. The methodology can be extended to include monitoring of an adaptive plan (see Walker et al., 2001; Haasnoot et al., 2013) for practical implementations of adaptation strategies. These features are important for identifying robust adaptation strategies – since they need to perform adequately across a range of uncertain future scenarios. This is especially true for the case study we are addressing – where long design lifetimes of infrastructure combined with short term planning horizons lead to certain assets being "under designed" for future climatic conditions. This is true for both ports (Koppe, 2018; Becker et al., 2018) and rail networks (Lindgren et al., 2009). Another key feature of the method are adaptation tipping points (ATP) - the point at which the system no longer performs "acceptably" according to predetermined criteria (Kwadijk et al., 2010). Adaptation tipping points are intended to be less impacted by the data in specific scenarios, instead identifying at what point a policy or system will fail. In the context of the adaptation pathways approach, ATP are used to identify at which point the next action is required.

A variety of approaches towards "light" applications of robust decision making were screened in order to inform and refine our framework. For example, McDaniels et al. (2012) develop a judgement-based approach that incorporates the use of Likert scales to identify robust forest management strategies in British Columbia. Kapetas & Fenner (2020) develop a simplified pathways diagram showing the implementation times of adaptation measures based on both tipping points and lead times, while also considering co-benefits of the measures in their assessment. Finally, Lawrence et al. (2019) also use a simplified timescale (short-medium-long term) to represent their pathways, and employ a multi-criteria assessment to evaluate the pathways.

The resulting framework of the outlined approach conceives of adaptation planning as a set of actions over time, visualised as multiple pathways across a horizontal time axis. For our purposes, we have developed an adaptation pathway method which suits the conditions of the case study. Very often pathway approaches are used for a specific context and location (e.g. Kapetas & Fenner, 2020; Lawrence et al., 2019, Deltares, 2017). One objective of this case study was to develop an approach which is applicable for a high-level perspective and combines elements of the overall logistical network (i.e.

port infrastructure, hinterland transport network, and the supply chain), Furthermore, an important aim of our approach was to incorporate stakeholder input via participatory processes – for example through an expert workshop as well as an online survey.

The framework involves the five following steps:

1. **Decision context and situation analysis**: First, the decision context of the area is outlined, presenting the adaptation situation. A situation analysis follows, highlighting the climate risks and damages in the port, transport network, and supply chain.
2. **Strategy building**: Adaptation measures are identified and assessed against key performance criteria. This includes their operational focus, which climate risks they address, as well as which timeframes are appropriate for implementation. The measures are then bundled according to their operational focus.
3. **Adaptation tipping point**: Using the climate risks identified in step 1, we then identify the adaptation thresholds/tipping point to be used in the development of the pathways.
4. **Adaptation pathways**: The bundles of adaptation measures are assessed according to their potential to reduce future climate damages across four key hazards. The bundles are then sequenced according to the established timeframes and using the adaptation tipping points.
5. **Multi-criteria analysis**: Finally, the pathways are assessed using a multi-criteria analysis in order to allow for a discussion comparing and contrasting the benefits and pitfalls of each approach.

Figure 2.2.6 below presents our application of the adaptation pathways approach:

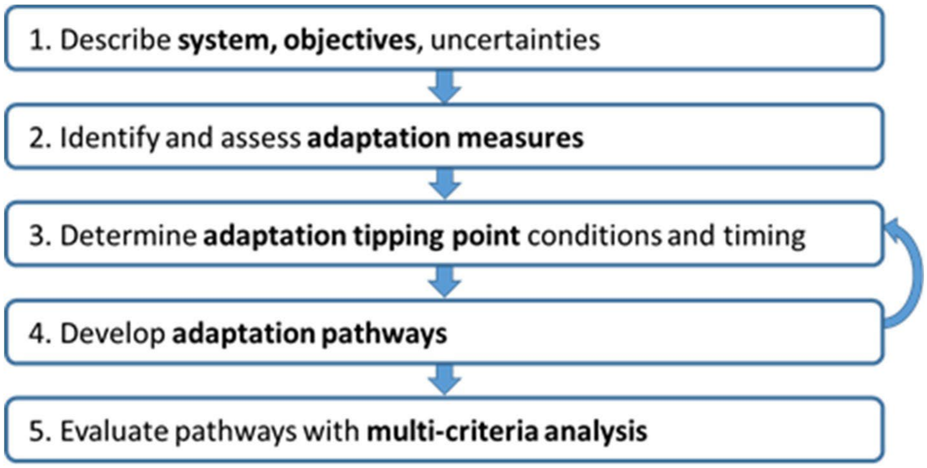

Figure 2.2.6: Adaptation pathways step by step process developed for the study

The study is based on literature reviews of the situation and decision context; climate impacts on ports, transport infrastructure, and supply chains; adaptation options; and existing adaptation policies and strategies. The review included scientific and grey literature. With regards to seaports, Becker has written extensively on climate impacts and adaptation for ports and shipping (Becker et al., 2012; Becker et al., 2013; Becker et al., 2018), and the World Association for Waterborne Transport Infrastructure recently released a comprehensive report on adaptation planning for ports and waterways (PIANC, 2020). With regards to the transport network, detailed reports have been produced on adaptation in Europe (EEA, 2014; Aparicio, 2017), with a recent UNECE report covering the global scale, with many relevant adaptation case studies (UNECE, 2021). Comprehensive studies of climate impacts and adaptation for the supply chain is more limited (Ghadge et al., 2019), with most studies focused on specific case studies, however Dasaklis & Pappis (2013) provide a broad overview of climate impacts to supply chain management.

Additionally, the study developed an online survey that was circulated to relevant experts with knowledge of ports, transport networks, and supply chains. These included practitioners, researchers, and policymakers. The input gathered from the survey fed into the strategy building step, and allowed us to build on the information gathered from the literature review. Finally, these experts were invited to an online workshop on the topic of "Addressing climate change in European supply chains." Relevant aspects from the overall study on industry and business were presented, including adaptation to transboundary risks, supply chain shocks in European industries, and impacts of river flooding on road transport. The adaptation pathways approach was also presented, and stakeholders provided feedback on the bundles and pathways, as well as offering suggestions for further considerations and relevant policy aspects.

Results

Decision Context and Situation Analysis

The North Sea is situated in northern Europe, bordered by Norway, Sweden, Denmark, Germany, Belgium, the United Kingdom, and the Netherlands. According to the EU's Interreg programme: "The North Sea Region distinguishes itself by its economic power, good infrastructure, a highly qualified workforce and an efficient management of environmental risks. Protecting the sea and the coast is also an important topic. Sustainable transport plays a significant role as the North Sea Region with its ports is the most important logistical hub in the EU." (Interreg, 2014).

For the purposes of this study, we will use examples from North Sea ports and their associated transport and supply chain networks to illustrate the general situation in the region. This includes the ports of Rotterdam, Hamburg, and Bremerhaven. The transportation networks and supply chains associated with these ports stretch from the coastal regions throughout the rest of Europe. These port, transport, and supply chain networks face a range of challenges with regards to climate change, and in turn employ a broad range of adaptation measures and strategies to respond.

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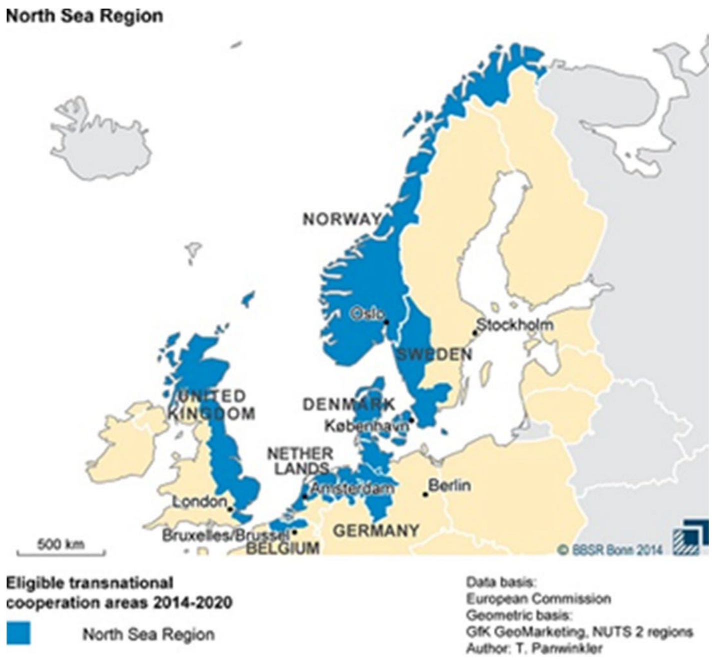

Figure 2.2.7: Map of North Sea Region (Source: Interreg, 2014)

Institutional, policy, socio-economic context

Climate issues have not traditionally been a high-priority issue for ports. According to the European Sea Ports Organisation (ESPO), climate change became one of the "Top 10" issues for ports for the first time in 2017 (ESPO, 2019). However, according to ESPO's environmental report, 75% of respondents in 2019 say that their port "considers climate change adaptation as part of new infrastructure development projects."

The environmental focus of European regulations and policies related to ports is generally oriented towards pollution issues, including not only the reduction of greenhouse gas emissions, but also the reduction of noise, water, and soil pollution. A Communication from the European Commission in 2013 (EC, 2013a) aimed to connect ports to the trans-European transport network (TEN-T), while also modernizing port services and operations, and raising the environmental profile of ports. The latter of these only briefly mentions emission reductions, and adaptation is notably lacking. More recently, in 2016, the Commission launched a project within its Horizon 2020 research programme titled "PortForward: Towards a green and sustainable ecosystem for the EU Port of the Future." The project objectives include the development and adoption of smart logistics solutions (i.e. digitalization), as well as green technologies, and the interconnectedness of ports and transport modes (PortForward, 2018). In sum, we observe that European policies on ports do not yet appear to be major drivers of adaptation efforts at port. Port adaptation, therefore, rests mostly in the hands of the

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port authorities and companies operating within and surrounding the port, with important input coming from local, regional, and national governments.

As for transport networks and supply chains in Europe, the key policy is the aforementioned TEN-T network, which implements and develops European rail, road, waterways and other transport nodes to “close gaps, remove bottlenecks and technical barriers, as well as to strengthen social, economic and territorial cohesion in the EU.” In addition to increasing efficiency and interconnectedness, the policy aims to increase resilience of infrastructure to climate change and deploy the latest technology and digital solutions (EC, 2013a). The updated EU Adaptation Strategy (EC, 2021a) also highlights that “To minimise the risk of disasters and be cost-effective over its lifetime, infrastructure investments should be climate resilient,” with climate-proofing guidance already in place for new projects. These guidelines will be extended to existing projects as well as other EU funds. Finally, the new Adaptation Strategy points to the importance of nature-based solutions in infrastructure planning.

The socio-economic importance of ports, hinterland transportation networks, and their supply chains to the cities and countries in which they are located cannot be understated, not to mention their integral role in linking the modern global economy. In Rotterdam, for example, the Port is responsible for 385,000 jobs, producing an added value of over 45 billion Euros. This represents 6.2% of the Dutch GDP – hardly an insignificant value (Port of Rotterdam Authority, 2019). The Rhine River stretches from its source in the Swiss Alps through Austria, France, Germany, and the Netherlands where it empties in the North Sea at Rotterdam. It is the most important inland waterway in Europe, accounting for about 75% of German inland water transport and 6% of German total cargo transport (UNECE, 2021).

Climate impacts for North Sea ports and transport networks

As a predominantly coastal area, the North Sea region faces climate risks from sea-level rise, increased coastal flooding due to more frequent and intense precipitation and storms, and higher water and atmospheric temperatures (Climate-ADAPT). Due to their low-lying nature, port operations and the hinterland logistic infrastructure are at particular risk not only from sea-level rise, but also higher storm surges, increased precipitation and flash floods, increased summer temperatures, and fluctuations in wind speeds (Becker et al. 2013; Becker et al., 2012; UNECE, 2021). Increased temperatures (both mean and extreme temperatures) will impact the need for more heating and cooling of port buildings, goods at the port and at storage areas, or within the transport network (Wenzel and Treptow, 2014; UNECE, 2021) and increase the risk of road degradation and rail buckling (UNECE, 2021). Finally, temperature and precipitation changes can cause more frequent equipment failures, changes to how cargo is handled, and changes to sediment loading and dredging (Becker et al., 2012; UNECE, 2021). Rail

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and road networks as part of the supply chain are especially impacted by extreme events, such as flooding, heatwaves and storms (EEA, 2014; UNECE, 2021).

The ports and transport networks in the North Sea region will all experience these impacts to varying degrees. Because of the generally short term planning horizons for ports, rails, roads, and logistics and the long lifespan of the infrastructure, different elements of these systems will be protected to varying degrees from the aforementioned climate impacts (Lindgren et al., 2009; Koppe, 2018; Becker et al., 2018).

Table 2.2.9: Climate hazards and potential impacts for the supply chain network

Climate Hazard	Port area	Hinterland transport network	Supply chain
Sea-level rise and increased storm surges	· High waves that can damage the port’s facilities and ships · Transport infra- and superstructures in the port get flooded · Coastal erosion at or adjacent to the port · Deposition and sedimentation along the port’s channels · Overland access (road/railway) to port/terminal will be limited due to flooding	· Overland access (road/railway) to port/terminal will be limited due to flooding · Rail tracks washed out by heavy rain can no longer be used by fully loaded trains.	· Potential for dislocation of warehousing and storage due to extreme events · Extreme events lead to a need to reorient routing and scheduling

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Increased precipitation (river flooding, flash floods)	· Increased disruptions/standstill in terminal operations. · Capacity of existing drainage systems may be exceeded · Quay walls may be breached	· Rail tracks washed out by heavy rain can no longer be used by fully loaded trains. · Low road sections flooded and access to and from port is blocked. During winter, freezing of this additional precipitation can restrict traffic flow especially in morning and night.	· Extreme events lead to a need to reorient routing and scheduling
Fluctuations in average wind speeds	· Downtime in the port operation due to high winds · Degradation, failure of structures and equipment · Reduced regularity of the port	· Trees blown over in storms can damage the overhead lines and bring train traffic to a standstill for hours.	

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Increased summer temperatures (heatwaves, droughts)	· Degradation, failure of structures and equipment · Reduced asset lifetime · Increased need for air conditioning (and energy consumption) for offices and areas where machinery/cargo is kept · Reduced labour productivity and heat stress	· Increased rail buckling · for road infrastructure, excessive warmth during summer days may lead to road pavement degradation, asphalt rutting or thermal damage of bridges. For rail infrastructure, this may lead to track buckling, damageto infrastructure and overheating of locomotives or signalling problems. (UNECE) · Droughts may lead to lower water levels in inland waterways, disrupting transport	· Increased need for cooling of warehouses and infrastructure.
Sources	Yang et al., 2017; PIANC, 2020; Becker et al., 2013; Wenzel & Treptow, 2014	UNECE, 2021; Christodoulou & Demirel, 2018; EEA, 2014; Dasaklis & Pappis, 2013	Dasaklis & Pappis, 2013

Current and future adaptation in the region

Ports in the North Sea Region are already heavily invested in adapting to the changing climate. The approaches taken vary within the region, in response to the different challenges faced at the ports. In Rotterdam, where the main climate concerns are sea-level rise and increased storms, investment is focused primarily on flood risk management (Eisma, 2016). At the Port of Hamburg, the smartPORT concept acts as a

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driver for digitalization efforts within port infrastructure (HPA, 2016). Digitalization can be important in helping ports (as well as the transport network and supply chain) to respond to changing climate conditions. In Bremerhaven, the adaptive capacity of the port and related infrastructure is considered to be "high," while transportation infrastructure is only "medium" meaning increased vulnerability to the impacts of climate change (Osthorst, 2016). One challenge for adaptation at ports is tied to the unclear responsibilities between the various actors at the port (i.e. operators, port authority, municipality), which leads to concerns over the implementation of adaptation measures.

At the European level, adaptation of transport networks occurs through both the EU Adaptation Strategy and the implementation of the TEN-T network. The TEN-T Guidelines (EC, 2013b) note that all development should consider impacts of climate change as well as natural disasters on infrastructure, and that future planning and development should consider potential climate vulnerabilities. Funding of projects is dependent on consideration of such factors. However, it has been noted more recently that little consideration has been given to adaptation needs of the core network and remain focused at the project level (Aparicio, 2017). At the national level, an EEA review of national adaptation strategies notes that the transport sector is specifically mentioned in numerous plans (including the Netherlands, Germany, Denmark, and Belgium, but not Sweden and Norway), however it is not yet perceived as a "central issue" (EEA, 2014). A 2018 review of the EU Adaptation strategy noted that long-term infrastructure investments were needed to improve transport resilience (EC, 2018). In an assessment of adaptation actions for transport across Europe, Aparicio (2017) notes that adaptation approaches take a short-term perspective, focused on maintenance and rapid recovery. Deployment of ICT in transport (i.e. digitalization) is highlighted as a key measure (and one that can have important co-benefits for mitigation objectives).

Strategy building

The identification of adaptation options for the study was achieved primarily through a detailed literature review. This was bolstered through the use of an online survey circulated to experts, in order to gather feedback on the options identified, and their performance against various climate hazards.

A comprehensive assessment of port adaptation measures is included in Yang et al. (2017), which focuses on a case study of 14 major container ports in Greater China. The climate risks identified in the study are generally comparable to those faced by ports in the North Sea Region. In highlighting the challenge of balancing both short-term and long-term solutions, Becker et al. (2018) points to the importance of incorporating both "hard" and "soft" adaptation measures in future planning. More recently, The World Association for Waterborne Transport Infrastructure published its report on adaptation planning for ports and inland waterways (PIANC, 2020), which points to a wide range of

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potential physical, social, and institutional measures that can be used to increase resilience.

As for the transport network and supply chains, Lindgren et al. (2009) present lessons learned from adaptation of the Swedish railway system, with the establishment of tree-free zones and improved drainage systems specifically highlighted. The EEA (2014) produced a detailed review of adaptation in the transport sector in Europe. Low-regret approaches are noted as being preferable in practice due to their co-benefits for other sectors and generally low costs. Specific measures mentioned include the development of early warning systems for extreme events, increasing multi-modality, and an increased focus on digitalization. Aparicio (2017) echoes the importance of ICT and digitalization, but adds that future adaptation planning for transport should incorporate future development of low carbon mobility and non-motorised transport modes, in order to align with European mitigation strategies. Additionally, the UNECE (2020) has also produced an extensive overview of climate impacts and adaptation options for transport networks and nodes, including case studies on the German transport system and highways in the Netherlands. Finally, Dasaklis & Pappis (2013) provide helpful perspectives on supply chain management in light of climate change, proposing adjustments to “Just-In-Time” systems and the regionalization of supply chains as strategies to improve resilience.

Through the literature review, a set of 26 measures were identified that addressed the various climate hazards and potential threats across ports, transport networks, and supply chains. These measures were then assessed against a set of criteria:

- The local focus of the measures (e.g. port infrastructure, transport network)
- The climate change hazard addressed (e.g. sea-level rise, increased temperatures)
- The type of measure (e.g. hard, soft, green)
- The availability of the measures (i.e. When is the measure ready to use, due to technological development?)
- The relevant timescale of the measure (i.e. at what timescale does the measure need to be implemented, relative to the climate hazard it addresses?)

Following this assessment, the measures were “bundled” according to six orientations: port infrastructure, hinterland transport infrastructure, green/nature-based solutions, logistics and supply chain digitalization, supply chain management, and “soft”/risk management measures. The table below presents an overview of the outcome of the bundling process:

Table 2.2.10: Bundles of adaptation measures (Aparicio, 2017; Becker et al., 2013; Dasaklis & Pappis, 2013; EEA, 2014; Lindgren et al., 2009; PIANC, 2020; The Climate Group, 2008; UNECE, 2021; Wenzel & Treptow, 2014; Yang et al., 2017)

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Port infrastructure measures	• Raise port/critical infrastructure elevation • Build new breakwaters or increase breakwater dimensions • Increase quay height • Protect coastline and increase beach nourishment programs • Move facilities away from existing locations which are vulnerable to climate change risks and impacts • Modernise drainage systems/increase rainwater discharge capacity • Secure and weatherproof structures, equipment, cargo
Hinterland transport infrastructure	• Improve and diversify land connections to port/terminal • Modify rail and road infrastructure to increase resilience • Transportation assets placed in locations where vulnerability assessments have been carried out • Integration of data from weather surveillance systems in route planning
Green/Nature-based solutions	• Adapted vegetation management along roads and rails • Modernise drainage systems/increase rainwater discharge capacity • Protect coastline and increase beach nourishment programs
Logistics/supply chain digitalization	• Adoption of smart logistics systems • Using weather data in supply chain management • Databases for natural hazard management systems for transport

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Supply chain management	Regionalization of supply chains Adjustments of Just-in-Time systems, incl. storage Use of different suppliers Multichannel logistics
Soft/risk management measures	Create financial instruments to support adaptation Enhance emergency evacuation plans Consider adaptation in long-term plans Improve decision support tools and information Include climate impacts in risk management systems – e.g. selection of transport mode

In order to validate the selection of measures, we developed an online survey that was circulated to experts with knowledge of ports, transport, and supply chains. The survey asked for respondents to provide: (1) feedback on the climate risks addressed by the measures in each bundle, and (2) a qualitative cost assessments of the measures (on a scale of 1-5). Finally, respondents had an opportunity to provide general feedback on the bundles and measures, and note if there were any important gaps. On the whole, the responses generally confirmed the information that had been gathered from the literature review, particularly with respect to the climate risks addressed by the measures. The cost information was especially helpful in progressing our study, as such information is difficult to come by in the literature. However, it is important to note that we collected qualitative cost information, and that research including quantitative cost assessments remains a gap at this stage.

Adaptation tipping points

To move from the identified measures and bundles towards developing a sequence of adaptation options in addition to the measures already implemented today[4], we must identify the adaptation tipping points (ATP) for the study. The ATP is reached when the system (in this case the supply chain network) no longer performs “acceptably” (Kwadijk et al., 2017). The ATP can be defined in a variety of ways. One approach is to set the ATP to occur when a specific flood risk level is reached (i.e. 1/300, 1/1,000, etc) which is less

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[4] Current adaptation levels are already meant to protect against some future changes, we therefore assess additional adaptation needs.

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suitable for this study as a range of climate hazards are covered. For purposes of simplicity, and for ease of stakeholder engagement as discussed above, the ATP was set at the current situation. If damages exceed the damages which appear today, we assume an ATP is reached and additional adaptation activities are necessary (Deltares, 2017).

Adaptation Pathways

Following the establishment of the adaptation tipping point (ATP), the study moved towards the development of adaptation pathways. The first step involved a qualitative assessment of future damages to the supply chain network based on the reviewed literature (e.g. UNECE, 2021; PIANC, 2020; EEA, 2014). The four key climate hazards (see Decision Context and Situation Analysis) and the associated damages were scored for three time frames: short term (present-2050), medium term (2050-2080), and long term (2080-2100, and beyond). Next, the bundles of measures were assessed according to their potential to reduce damages from each of the climate hazards. This was achieved through a combination of expert judgement, information gained from the literature review, and feedback obtained through the stakeholder survey.

With this initial qualitative assessment of damages and potential of bundles to reduce damages, we moved towards laying out sequenced adaptation bundles to form pathways. A set of five potential pathways to approach adaptation for port infrastructure, transport networks, and the supply chain was developed. With bundles like port infrastructure measures and digitalisation most suitable in later timeframes, and "soft" risk management measures suitable as immediate, no-regret options, we developed five narratives for the pathways.

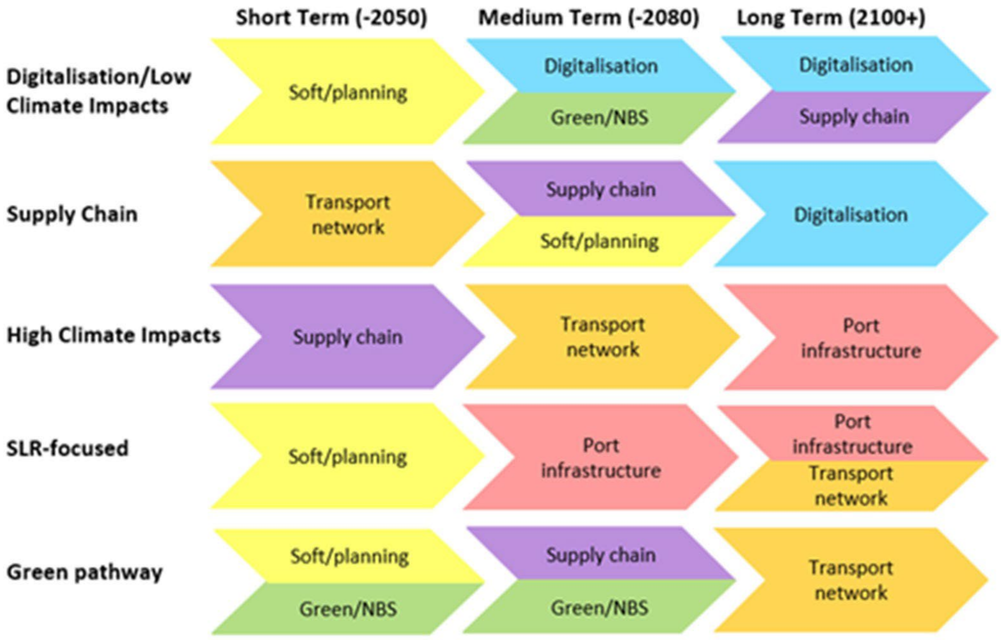

Figure 2.2.8: Adaptation pathways developed for case study

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Pathway 1 (Digitalisation and low impacts): This pathway is suitable for a supply chain network with relatively advanced adaptation measures in place. The port is **likelyalready protected against SLR**, and **transport/supply chain issues are already largely incorporated in planning**. In the short term, the focus is on developing "soft" risk management measures, which can be maintained and adapted over time. In the medium term, the focus shifts to digitalisation measures for logistics management, as well as green/NBS measures as initial responses to climate impacts like heavier precipitation. Finally, digitalisation measures are supplemented with supply chain management measures in the longer term.

Pathway 2 (Supply Chain Focus): This pathway is suitable for a supply chain network that may have relatively developed adaptation strategies for port infrastructure (especially against sea level rise), but **has not considered impacts to hinterland transport and the supply chain**. As such, it starts directly in the short-term with (technical) improvements to the transport network. In the medium term, it complements an improved transport network with soft risk management measures and measures oriented towards supply chain management. Finally, it implements at this time well-established digitalisation measures in the long term.

Pathway 3 (High Impacts Pathway): This pathway is suitable for a supply chain network that is expected to face **high climate impacts across all elements of the network**. In the short term, it implements supply chain management measures as a no-regret option. These are complemented in the medium term by developing adaptation measures for the transport network. In sequence, these two bundles are relatively effective at addressing damages from climate impacts like increased wind speeds, precipitation, and higher summer temperatures. Finally, in the long term, port infrastructure measures are implemented to protect against heightened levels of sea-level rise.

Pathway 4 (Sea-level rise focus): This pathway is suitable for a supply chain network that may face **sea-level rise as a major climate impact in the nearer term**. In the short term, it adopts soft risk management measures as an initial response to other climate impacts. Already in the medium term, it needs to implement more costly port infrastructure measures. The implementation of port infrastructure measures in the medium term contrasts with the other pathways, where these are left until last. In the long term, it complements with measures oriented towards the transport network.

Pathway 5 (Green Pathway): This pathway is oriented towards a supply chain network with **a well-protected port** with **less existing focus on the resilience of its transport network and supply chain**. As such, green/NBS measures management are attractive in the short and medium term, complemented with soft risk management strategies early on. These measures in particular can show a delay between implementation and achieving the desired effect, so implementing them immediately, and over a sustained duration is beneficial. Additionally, in the medium term, the focus is on supply chain

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management measures, which are then complemented with transport network measures in the long term.

To ensure that these pathways not only made sense in terms of the sequencing of options, but also in terms of their damage reduction potential, they were assessed according to the ratio of damage reduction to expected climate impacts in each timeframe. In each case, the ratio was below 1, meaning that the adaptation tipping point had been reached, and that new measures were necessary.

After a set of pathways was prepared, a stakeholder workshop was organized in collaboration with project partners Deltares and the University of Graz. Our study of adaptation pathways for ports and supply chain networks was presented, in order to gather further inputs and feedback from stakeholders related to the measures, bundles, as well as the proposed pathways. This was an important step to validate the pathways and to be able to move towards an assessment and comparison.

Multi-criteria analysis

Combining the input from both the online survey and the stakeholder workshop, we employed a multi-criteria assessment (MCA) to examine other aspects of the pathways (Haasnoot et al., 2013; Deltares, 2017; Lawrence et al., 2019). In addition to the overall damage reduction potential, the pathways were each assessed according to the following criteria (BASE, 2014; Deltares, 2017; Lawrence et al., 2019):

- **Damage reduction**: qualitative assessment of the potential of the measures to reduce damage for each of the climate impacts
- **Implementation feasibility**: ease of implementation of the adaptation measures, including legal, technical, social, institutional, political, and financial considerations
- **Ease of maintenance**: ability to monitor and maintain the measures in an efficient and cost-effective manner
- **Flexibility**: this represents the potential for adjustments due to different climate scenarios or socio-economic developments
- **Co-benefits**: this criteria broadly encompasses potential socio-economic and environmental co-benefits that may emerge as a result of implementing the adaptation measures.

For each bundle of measures, a score from 1-5 was assigned for each of these criteria. For example, the bundle of port infrastructure measures scored 1 for their Flexibility, as these measures involve significant physical and structural changes that are difficult to reverse or alter. On the other hand, the soft/risk management bundle scored 5, since these measures are easily modified across a range of future scenarios. The bundle scores were then summed for the five pathways, in order for each pathway to reach a total combined MCA score. As a final step, the criteria were assigned weightings in order to assess the performance of the pathways across both a low and high climate scenario. In

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the high scenario, damage reduction for the four climate impacts was weighted more heavily, while other aspects like flexibility and co-benefits were weighted lower. A sensitivity analysis was also performed, to determine how the MCA results and ranking vary when the relative importance of the criteria is changed.

At this stage, the five pathways have each received two MCA scores (one for the High scenario, one for the Low scenario). Using the cost information from the survey (cost assessments for individual measures were summed for each bundle, and then normalized to a 1-5 scale), we were able to assign qualitative cost values to each pathway. The cost information was left out of the MCA, since the figures are purely qualitative, and do not represent "real" cost information. However, following the MCA, the scores were combined with the costs, in order to determine a ratio that can be compared across the pathways. The results of the MCA process can be seen in the table below:

Table 2.2.11: Multi-criteria analysis scores

	SLR/storm surges	Wind	Precipitation	Temperatures	Implementation feasibility	Ease of maintenance/ regulation	Flexibility	Co-benefits
Pathway 1	2	2	4	4	5	5	5	5
Pathway 2	1	4	4	4	4	5	4	3
Pathway 3	5	5	3	3	1	1	1	1

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Pathway 4	4	1	1	1	1	1	2	2
Pathway 5	2	5	5	5	5	4	4	5

Table 2.2.12: Weighted multi-criteria analysis scores for high and low climate scenarios

	MCA score - Low Scenario	MCA score - High Scenario
Pathway 1	4,12	3,82
Pathway 2	3,82	3,77
Pathway 3	2,20	2,60

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Pathway 4	1,62	1,69
Pathway 5	4,38	4,25

The results of the MCA show that Pathway 5 (Green Pathway) scores highest in both the high and low climate change scenarios. This is largely due to its strong scores in addressing non-SLR climate impacts, as well delivering high co-benefits and implementation feasibility. Close behind, Pathway 1 (Digitalisation and low climate impacts) and 2 (Supply chain focus) rank second and third, respectively. These pathways also score highly for damage reduction, while also being relatively easy to implement and maintain, and offering important flexibility. Pathway 3 (High climate impacts) ranks fourth and somewhat lower than the rest, as it scores poorly in the non-damage related criteria. Pathway 4, focused on sea-level rise, ranks last due to its weaker performance against other climate impacts as well being difficult to implement and maintain. We note that the rankings of the pathways are unchanged in both the high and low scenarios, and that the sensitivity analysis shows that changing the weightings of the criteria does not significantly affect the results either.

Additionally, we examined the MCA score in relation to the assessed costs. The results show Pathway 1 with the best combination of high MCA score and lowest costs. The results for Pathway 2 and 5 are very close to Pathway 1. As discussed, Pathway 5 shows the highest MCA score but shows slightly higher costs than Pathways 2 and 1. The assessment shows lower MCA scores and higher costs for Pathways 3 and 4.

Conclusion

The case study above presents the use of a modified adaptation pathways approach towards a high-level assessment of climate adaptation for a supply chain network. The

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methodological approach demonstrates how stakeholders and experts can be involved in the process in multiple stages, in order to develop a robust approach to adaptation. Furthermore, this work developed an approach which is suitable for the assessment on a broader level (regional or national). It would be interesting to elaborate further on the development of an adaptive plan that not only sketches how measures in the preferred pathway can be implemented e.g. clarify responsibilities, budgets, but also lays out a monitoring strategy that allows for adjustments to the plan depending on changes to the climate or socio-economic conditions. Furthermore, another additional task could be to back up the semi-quantitative cost estimation with a quantitative cost assessment. In the stakeholder workshop, questions on the differentiation between upfront investments and continuous investments were also highlighted. Unfortunately, these aspects were beyond the scope of this case study. Further research could also look into the definition of ATP especially if a number of heterogeneous entities are included in the assessment.

○ 2.3 Policy effectiveness in insurance (Lead: IIASA)

Introduction

This study assesses the macroeconomic impacts of different policies with regard to flood insurance. In COACCH Deliverable 3.2 (D3.2) it is shown that climate and socioeconomic change will pressure the functioning of flood insurance markets in some regions of the EU. This is driven by an increase in unaffordability of premiums and a declining demand for coverage, which varies for scenarios of climate and socioeconomic change. Besides this, it was found that certain types of flood insurance mechanisms, that are already applied in some EU-countries, are better able to cope with the pressure posed by increasing flood risk. Based on these observations, D3.2 concluded with a brief policy proposal, where we recommend a limited degree of risk-sharing, a public reinsurer, and insurance purchase requirements. In this deliverable we aim to further assess the policy effectiveness of these recommendations using the macroeconomic CGE model COIN-INT. This model is described in detail in D3.4 (section 5.1) and the adapted regional and sectoral aggregation for the purpose of the insurance analysis is laid out in the method section below.

Currently many European countries ensure compensation payments to private households funded by disaster funds or other public budget items. While the resources of these funds usually suffice in average years, they are quickly used up when a big disaster occurs. In the context of increasing flood risk due to climate change, also average years might challenge budgetary coverage in the future. Insurance can be an effective alternative financing mechanism, however limiting costs for policyholders and maximizing societal coverage against flood risk pose significant challenges (Tesselaar et al., 2020). In particular, increasing premiums can discourage households from obtaining insurance coverage when this is optional, largely because subjective flood risk is found to often fall short compared to objective risk when dealing with low-probability high-impact events (Kunreuther, 2015). This may require governments to more often provide damage compensation to uncovered households in the future. Uncertainty regarding the required level of damage compensation implies that public budgets may incur fiscal stress when not preparing for higher costs. Increasing the insurance penetration rate may reduce potential problems for the government budget and enhance overall economic performance. Improving insurance uptake can be attained by reducing or limiting the rise in premiums, by making coverage mandatory, or including it in general homeowner insurance policies.

The literature body that focuses on insurance in the climate change debate as an essential strategy to cope with damages from several weather extremes has been growing. Many aspects surrounding the policy debate of flood insurance have been discussed. Several studies investigated short term effects on macroeconomic outcomes given the availability of insurance. More recently, the discussion has moved towards the design of an insurance against natural hazards with a special focus on risk-sharing possibilities. Insurance market systems vary substantially between countries and span from primarily publicly organized systems to entirely private systems, both of which have their drawbacks. The bottom-up literature comes to the conclusion that a risk-sharing approach is the most beneficial as well as the most resilient to climate change, based on measures such as affordability, insurance uptake and coverage (Hudson et al., 2019). However, these are partial equilibrium or optimization models that do not take into account the government sector and thus neglect macroeconomic feedback effects and their implications for total welfare. Hence, there is a lack of comprehensive impact assessments of flood risk recognizing the role of different actors.

We thus aim to evaluate different mechanisms to insure against flood risk within a Computable General Equilibrium (CGE) framework to analyze both direct and indirect effects on macroeconomic indicators and the public budget. In the context of socioeconomic and climate change, we investigate which insurance scheme yields the lowest overall macroeconomic costs. We therefore soft-link the result parameters of a partial equilibrium model of the insurance sector to the CGE model by implementing current insurance markets for each country and two stylized markets involving a higher degree of risk sharing. We then evaluate the alternative insurance scenarios withrespect to the macroeconomic feedback effects as well as the effects on the public budget. While the calculation of insurance parameters up to 2050 is based on a dynamicmodel, the CGE model is a static-comparative model and thus only accounts for the resulting parameters in 2050. Hence, the different scenarios do not cover the implications of different insurance mechanisms on dynamic elements such as the speedof recovery or capital accumulation, but only the effects of a long run equilibrium in 2050. The modelling of the insurance markets is limited to the majority of EU countriesplus the UK, but flood damages occur in all European regions.

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Method

For this study we apply three models, the partial equilibrium model of the flood insurance sector (DIFI) (Hudson et al., 2019), the global hydrological impact model GLOFRIS (Ward et al., 2017; Winsemius et al., 2016), and the general equilibrium model COIN-INT (see D3.4 for a detailed description). Figure 2.3.1 gives a conceptual overview of the interaction of the applied models and which type of data is used for further procedure in the subsequent model. As the applied models are described in detail in earlier deliverables of the COACCH-project (DIFI in D3.2; GLOFRIS in D2.3; COIN in D3.4), this section is limited to the description of the model changes made to facilitate the exchange of input data, as well as the adjustment of regional aggregations in COIN-INT to more accurately assess results for EU-countries.

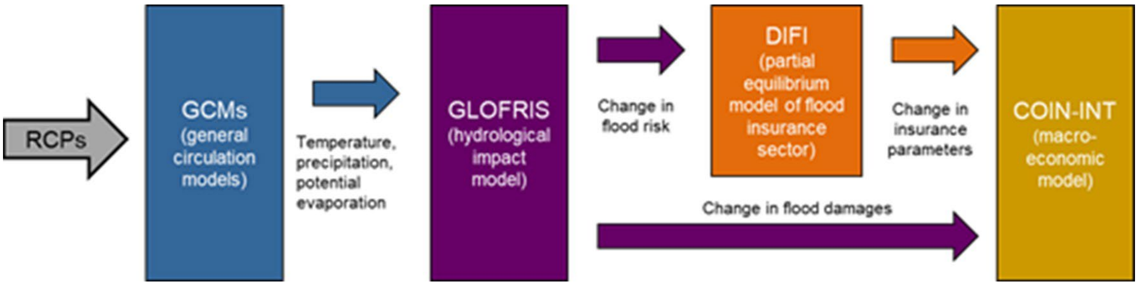

Figure 2.3.1: Conceptual overview of the model chain from emission scenarios to macroeconomic analysis

Riverine flood risk input data from GLOFRIS

For the macroeconomic assessment of flood risk and flood insurance indicators we required expected annual damage (EAD) for individual countries. In the insurance sector model (DIFI), as presented in D3.2, the EAD was calculated using flood impacts for various return periods, which was derived from the global flood risk model GLOFRIS. As the flood risk data is used directly by the DIFI model and the COIN-INT model (see Figure 2.3.1), we replaced the flood impact data per return period in DIFI with the EAD data obtained from GLOFRIS. Therefore, the flood risk input data used by DIFI and COIN-INT is derived in exactly the same way.

The estimation of EAD in GLOFRIS uses the urban flood impacts per return period (2, 5, 10, 25, 50, 100, 250, 500, and 1000 years). How the flood impacts are determined is described thoroughly in D2.3. EAD is calculated using a fairly standard approach in flood risk modelling, which is to take the integral of the exceedance probability-impact curve, which can be written as:

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$$EAD = \int_{p=0}^{1} D_{\theta}(p)dp$$

(1)

In this formula, D is the urban flood damage, θ is the vulnerability, and *p* is the annual probability of non-exceedance, which is the inverse of the protection standard. To account for the regional protection standard, the risk curve is truncated at the exceedance probability of the protection standard, which is expressed as a return period. The definite integral is estimated using trapezoidal approximation. Finally, as actual protection standards are not available for all regions, this is modelled using the FLOPROS modelling approach (Scussolini et al., 2016). For more detailed information regarding the calculation of EAD in GLOFRIS, we refer to Tiggeloven et al. (2020).

As an input variable for the DIFI model, EAD is derived on NUTS2-level for EU regions and the UK. Since the estimation of EAD within the DIFI model is no longer required, the flood risk module of the DIFI model, as explained in D3.2, is not used for this study. Therefore, flood risk data flows directly into the insurance and behavioral models, respectively, which are applied to calculate future flood insurance premiums and insurance uptake, as described in D3.2. For the COIN-INT model, the EAD data is then aggregated over NUTS2 levels and provided on a national level.

Updated region aggregation in COIN-INT

Concerning the regional aggregation of the model, we put a focus on EU regions as the DIFI model provides data on NUTS2 level for European countries. However, within Europe, there are also some regions, where there is no insurance market modelled, such as Malta, Albania, Switzerland or Norway. We aggregate regions according to similarities in economic structure and current insurance market systems. Thus, European countries constitute 21 regions in the model and the "rest of the world" is aggregated into five regions, such that computational issues deriving from too heterogeneous regions are avoided. The regions as well as the current insurance market structure and the assumed share of uncovered risk that is covered by the public funds are presented in Table 2.3.1.

Table 2.3.1: Aggregation of regions in COIN_INT and allocation of modelled insurance market.

Aggregated region	*Model code*	*Comprising GTAP regions*	*Current insurance structure*

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insurance market modelled	1	Austria	AUT	Austria	voluntary private market
	2	Germany	DEU	Germany	voluntary private market
	3	France	FRA	France	solidarity public structure
	4	UK	UKD	UK	public-private partnership
	5	Ireland	IRL	Ireland	voluntary private market
	6	Netherlands	NLD	Netherlands	voluntary private market
	7	Belgium & Luxembourg	BLU	Belgium, Luxembourg	solidarity public structure
	8	Spain	ESP	Spain	solidarity public structure
	9	Portugal	PRT	Portugal	voluntary private market

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10	Italy	ITA	Italy	voluntary private market
11	Greece	GRC	Greece	voluntary private market
12	Romania	ROU	Romania	solidarity public structure
13	Poland	POL	Poland	voluntary private market
14	Baltic states	BAL	Estonia, Latvia, Lithuania	voluntary private market
15	Northern EU	NEU	Denmark, Finland, Sweden	voluntary private market
16	North-Eastern EU	NEE	Czech Republic, Slovakia	voluntary private market
17	South-Eastern EU	SEE	Hungary, Bulgaria	voluntary private market
18	Southern EU	SEU	Croatia, Slovenia	voluntary private market

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No insurance market modelled	19	Rest of EU and EU candidates	REU	Malta, Albania, Cyprus, Rest of Europe (*Bosnia and Herzegovina, Macedonia, Serbia and Montenegro, Faroe Islands, Gibraltar, Monaco, San Marino*), Turkey
	20	Switzerland	CHE	Switzerland
	21	Rest of European countries	EUR	Norway, Rest of EFTA (*Liechtenstein, Iceland*)
	22	North America	NAM	USA, Canada, Rest of North America (*Bermuda, Greenland, Saint Pierre and Miquelon*)
	23	Latin America	LAM	Brazil, Mexico, Argentina, Bolivia, Guatemala, Honduras, Nicaragua, Peru, Rest of South America, Chile, Colombia, Dominican Republic, Ecuador, El Salvador, Paraguay, Uruguay, Costa Rica, Panama, Venezuela, Rest of Central America, Trinidad and Tobago, Caribbean (*Anguilla, Antigua and Barbuda, Aruba, Bahamas, Barbados, British Virgin Islands, Cayman Islands, Cuba, Dominica, Grenada, Haiti, Montserrat, Netherlands Antilles, Saint Kitts and Nevis, Saint Lucia, Saint Vincent and Grenadines, Turks and Caicos Islands, Virgin Islands (US)*), Jamaica, Puerto Rico

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24	Middle East and West Asia	MEA	Russian Federation, Kazakhstan, Belarus, Ukraine, Armenia, Georgia, Kyrgyzstan, Rest of former Soviet Union (*Tajikistan, Turkmenistan, Uzbekistan*), Rest of Eastern Europe (*Moldova*), Israel, Saudi Arabia, United Arab Emirates, Rest of Western Asia (*Iraq, Lebanon, Palestinian Territory, Occupied, Syrian Arab Republic (Syria), Yemen*), Azerbaijan, Iran, Bahrain, Kuwait, Oman, Qatar, Jordan, Pakistan
25	Asia and Oceania	ASI	China, India, Australia, New Zealand, Hong Kong, Singapore, South Korea, Japan, Bangladesh, Thailand, Indonesia, Vietnam, Malaysia, Taiwan, Philippines, Cambodia, Lao People's Democratic Republic, Rest of South-East Asia (*Myanmar, Timor-Leste*), Sri Lanka, Rest of South Asia (*Afghanistan, Bhutan, Maldives*), Rest of East Asia (*Korea, Macau*), Rest of Oceania, Nepal, Brunei Darussalam, Mongolia, Rest of the world (*Antarctica, French Southern Territories, Bouvet Island, British Indian Ocean Territory*)

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26	Africa	AFR	South Africa, Tunisia, Benin, Burkina Faso, Cameroon, Cote d'Ivoire, Ghana, Guinea, Egypt, Nigeria, Senegal, Togo, Tunisia, Rest of West Africa, Central Africa, Ethiopia, Kenya, Madagascar, Malawi, Mauritius, Mozambique, Namibia, Rwanda, Tanzania, Uganda, Zambia, Zimbabwe, Rest of Eastern Africa, Botswana, Morocco, Rest of South Central Africa, Rest of South African Customs Union, Rest of North Africa (*Algeria, Lybia*)

Source: GTAP v9 database (Aguiar, Narayanan, and McDougall 2016), countries in italics are aggregated in the original database; and Hudson et al. (2019) for current insurance market systems

*share describes how much of private flood damages are compensated by the government via compensation payments, based on literature search and publicly available data

Scenario framework and model implication of impact data and stylized insurance market systems

In general, in our analysis we always compare a *climate change scenario* to a *baseline scenario* of the same time period, which is 2050, to present relative differences between two potential states in the future.

The *baseline scenarios* in the CGE model incorporate socioeconomic developments according to the SSP storylines with the target of calibration being the reproduction of the annual SSP-specific GDP growth rates until 2050. For details of the baseline calibration, see D3.4, section 5.1.

The *climate change scenarios* entail impact data provided by the GLOFRIS model and are based on both different climate and socioeconomic developments (SSP-RCP). For the present analysis we considered the following combinations of SSPs and RCPs as well as General Circulation Model (GCM): RCP2.6-SSP1, RCP2.6-SSP2, RCP4.5-SSP2 and RCP6.0-SSP2 with HadGEM2-ES as the underlying GCM and RCP8.5-SSP5 with the five GCMs provided by CMIP5 project: HadGEM2-ES, IPSL-CM5A-LR, NorESM1-M, GFDL-ESM2M and MIROC-ESM. This allows us to account for both the uncertainty range across climate and socioeconomic developments as well as across climate modelling.. The exposure relevant for determining flood risk relies on the SSP scenarios: Exposed assets and household income growth are estimated using GDP growth, and exposed population is determined by population growth. For some regions projections suggest a reduction of damages despite the growing assets at risk, as the combination of certain climate scenarios and GCMs entail less precipitation and thus some regions might become dryer.

Flood impacts enter the model in three different ways: first, for every SSP-RCP combination, flood damages reduce the effectively usable capital stock by reducing the capital endowment of the private household representing the destruction of assets. The amount of damage is based on data from the GLOFRIS model and reflects average effects (EAD). Second, the costs of dikes and other flood protection structures are depicted as investments to maintain the current level of protection. Ongoing maintenance costs to prevent a decay of protective structures amount to 1% of annual investment costs and are modelled as consumption expenditures that crowd out other consumption possibilities.

The *climate change scenarios* in addition represent the different insurance market systems scenarios. There are three potential states for the insurance market system: the first is the current arrangement that is in place in each country, regardless which system this is. Hence, this provides results for a climate change impact assessment without changing the baseline insurance market system. The second state is a scenario, where each country has a Public-Private Partnership and the third state is a scenario with a solidarity public structure. In the results section, we will first analyse how riverine flooding affects the economy in 2050 with current insurance market systems and second compare this scenario to the other two climate change scenarios with changed insurance market systems.

We now describe the incorporation of the output of insurance market parameters of the DIFI model into the COIN-INT model. The different systems vary in terms of public and private consumption patterns (demand for insurance in the form of premiums and adaptation expenditures), investments for flood protection and transfers between the public and the private household.

Insurance premiums constitute consumption from the insurance sector that cover a certain amount of risk depending on the insurance market system. We assume that the risk that is covered by insurance does not imply any additional burden for the private household when engaging in reconstruction activities. In cases where flood damages exceed the risk covered by the premiums, to cover reconstruction payments the private household either needs to reduce its savings or receives compensation payments by the public household via transfers. These replacement expenditures then enter the model as consumption from the construction sector and are not welfare enhancing as they only restore the original state of welfare and individuals are not better off by this consumption. The transfers obtained from the public household range from zero to the

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total of uncovered risk, depending on the insurance market system and the common practice of the regions' government as to how it handles disaster losses. The applied rate of compensation for each country is stated in the last column of Table 2.3.1. Witha high rate of compensation, high uncovered risk in the voluntary systems leads to increased burden on the public budget and a readjustment of private spending. We hereby assume that climate-unrelated transfers are held constant and thus additional transfers induce a shift in public consumption. A low rate of compensation implies reductions of private savings, which are not implemented in the model but reported exogenously. Some insurance market systems incentivize policy-holders to engage in private adaptation measures, such as dry-proof or wet-proof measures. Adaptation measures decrease the extent to which the EAD translates into destruction of capital inthe first place and are also modelled as a shift in consumption patterns. The reduction of damages is calculated based on the benefit-cost ratio introduced in Aerts (2018). In a public-private partnership, the public household functions as the reinsurer of private insurers. In that case, there is a reinsurance premium paid by the private agent (i.e. theinsurance sector) to the public household in the form of a transfer.

Finally, another important assumption is that in the long run and on the aggregate level insurance companies' expenditures are completely covered by what they collect through premiums as they would otherwise go out of business. They charge an additional fee for administration costs and to cover their risk aversion to be prepared for unexpectedly large floods. Insurers base their premiums on the EAD, while pay-outs after a flood can clearly exceed or fall below premiums. As insurance is meant to spread the risk over time and space, damages in a certain year or location may exceed the collected premiums, however the insurer can recover from this loss by surpluses in other regions or in the past and future.

Results

This section presents the results for a climate change impact assessment with the current insurance markets in place for each relevant model region and with a change of insurance market systems towards a public-private partnership (PPP) and a solidarity market structure (SOL) in all relevant model regions. Each subsection first describes the direct impacts of climate change on damages and insurance parameters and second the macroeconomic implications thereof. Eventually we take a look at the overall impacts for the EU arising from flood risk under the different insurance market systems.

Impacts in a climate change scenario with baseline insurance market systems

Direct flood impacts

Direct costs associated with flood damages essentially drive the macroeconomic effects on GDP and welfare, however, the size of the damages in relation to the economy is crucial to understand relative changes. For the model regions in the CGE model, the direct flood damages from the GLOFRIS model in relation to GDP per region in SSP5 in

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2050 span between a minimum of 0.01% in the Netherlands and a maximum 0.43% in South-Eastern EU (SEE, including Hungary and Bulgaria) (see Figure 2.3.2). The damage numbers account for climate-driven changes on the one hand, and current protection standards on the other hand, resulting in a combination of exposure and adaptive capacity that eventually determines the vulnerability of regions. In general, low-income regions tend to be on the more vulnerable end of the distribution with the top countries being SEE, as just indicated, Romania, Southern EU (SEU, including Croatia and Slovenia), Poland, Portugal and North-Eastern EU (NEE, including Czech Republic and Slovakia). High-income countries, such as the Netherlands, the UK, Ireland and Belgium and Luxembourg (BLU) rank among the least vulnerable regions.

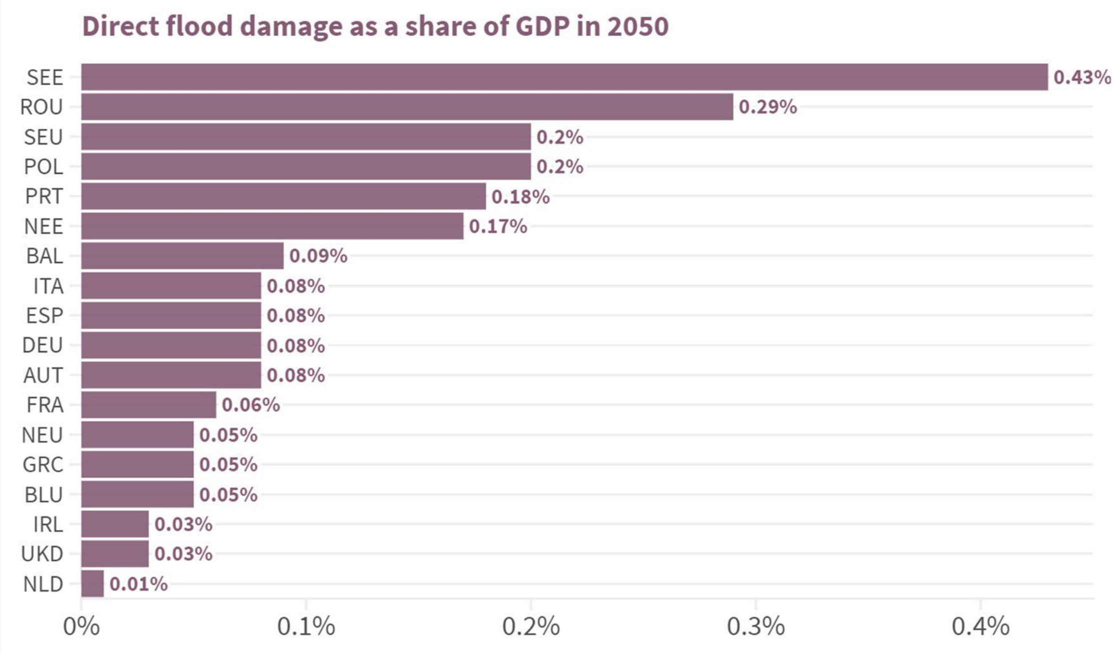

Figure 2.3.2: Flood damages in the RCP8.5-SSP5 scenario combination driven by the HadGEM2-ES GCM relative to the SSP5 GDP in 2050 for EU regions, sorted by size of the relative impact.

Considering that flood insurance systems remain constant over time, our results indicate that flood insurance premiums rise significantly towards 2050. This result is especially evident for more severe climate change scenarios, in particular the RCP8.5 scenarios, which is depicted in Figure 2.3.2. Also, insurance premiums are projected to rise more rapidly in high-risk areas for countries where these are risk-based, compared to countries where there is a higher degree of risk cross-subsidization. Consequently, rising premiums and lacking willingness to pay for coverage results in a decline of flood insurance uptake, which is most visible in certain high-risk regions, as well as regions where income per capita is relatively low. As a result of lower insurance penetration, the incentivized risk-reduction due to insurance is projected to become lower towards 2050. However, the risk-reduction effort by households incentivized by insurance policies is expected to increase following the model results of the DIFI model.

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Macroeconomic effects from flood impacts with baseline insurance market systems

The flood damage data and the resulting insurance parameters for 2050 as described in the previous section are now analysed in the CGE model. Figure 2.3.3 presents the macroeconomic effects on GDP and private and government welfare. At this point, we acknowledge that a differentiation between the welfare of a private household on the one side and the public household on the other side may be misleading as the public household's welfare is based on public consumption, which in turn reflects the provision of public goods and eventually benefits the private household. Nevertheless, this analysis also aims to determine who bears the burden of flood risk in different insurance market systems to identify potential policy responses for responsible actors. That said, we see that all macroeconomic indicators are affected negatively by flood risk in 2050 as compared to the baseline economy in the same year. In general, the effects are stronger for welfare than GDP and even more pronounced for government welfare than for private welfare. The macroeconomic outcomes reflect the patterns of the direct damages as presented in Figure 2.3.3 with the strongest effects observed for South-Eastern EU. We also find that the current insurance market system does not overcompensate the vulnerability of the countries in terms of their relative affectedness, i.e. Romania, while having a solidarity system in place, is still among the most strongly affected regions. However, for all regions with a solidarity system (France, BLU, Spain and Romania) the impact on private welfare is less pronounced than on GDP, which is not the case for the other regions. For the UK, the only country with a public-private partnership in the baseline, macroeconomic costs are the lowest in the EU with a reduction of GDP, private and government welfare equal to -0.03%.

Figure 2.3.3: Macroeconomic effects from flood damages with current insurance market systems relative to the baseline scenario in 2050 for EU regions; scenario combination: RCP8.5-SSP5 driven by the HadGEM2-ES GCM.

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In contrast to the two systems with certain degrees of risk-sharing mechanisms, the voluntary system results in substantial uncovered risk. This implies that private households either rely on public compensation payments to cover reconstruction payments or they need to reduce their savings to finance additional expenditures. The CGE model captures additional compensation payments in form of transfers from the public to the private household, whereas the reduction of savings is not depicted in the static CGE model, but would eventually have macroeconomic feedback through lower capital stocks in later periods as savings are used as investment. Figure 2.3.4 therefore shows the additional reduction of savings and the compensation payments by the government as an approach to measure the burden sharing between the two actors. The additional transfers entail increased pressure on the public budget, especially when other transfers are not cut for refinancing these expenditures. Consequently, the government welfare in Figure 2.3.3 is particularly affected in regions with a voluntary system and a high rate of compensating the uncovered risk, such as Germany, Italy, Poland, Ireland and South-Eastern EU. The macroeconomic impacts in regions with a voluntary system but very low rates of public compensation, such as Greece, the Baltic States, the Netherlands or Southern EU are likely underestimated due to the unembodied effect of reduced private savings.

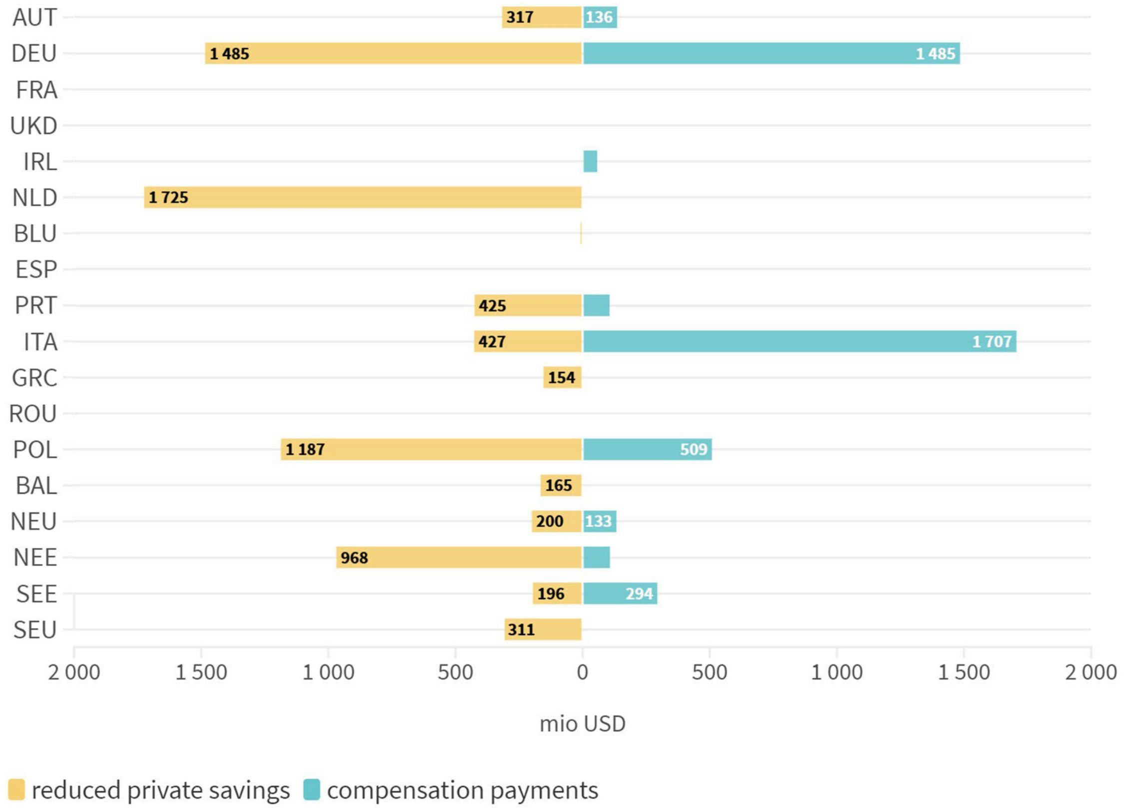

Figure 2.3.4: Burden sharing of uncovered risk with current insurance market systems with reduced private savings borne by the private household and compensation

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payments borne by the public household; scenario combination: RCP8.5-SSP5 driven by the HadGEM2-ES GCM.

Further focussing on the public household, government welfare decreases also as government income decreases from various sources. Overall, the net of tax income changes is negative in all regions with almost each individual tax income change being negative (except for slight increases of the trade tax income) (see Figure 2.3.5). Especially income from the factor tax is decreasing in the majority of regions. This is because the destruction of capital triggers a scarcity effect of that factor and thus implies its rent to increase. As a consequence, the employment of this factor decreases and thereby reduces the tax base for the factor tax. The destruction of capital and thus a means of production also decreases the overall output of the economy reducing the tax base for the output tax. Lower economic activity implies a lower use of intermediate input goods but also lower income for the private household, which reduces consumption and, associated therewith, the consumption tax income (the tax that is applied to all goods that are either used as intermediate input in production or for final demand use) for the government budget. The trade tax income change is only minor and direction depends on whether a country's reduction in exports or increase in imports prevail. In conclusion, lower income for the public household implies that the government agent's consumption necessarily needs to decrease as well yielding a reduction of government welfare.[1]

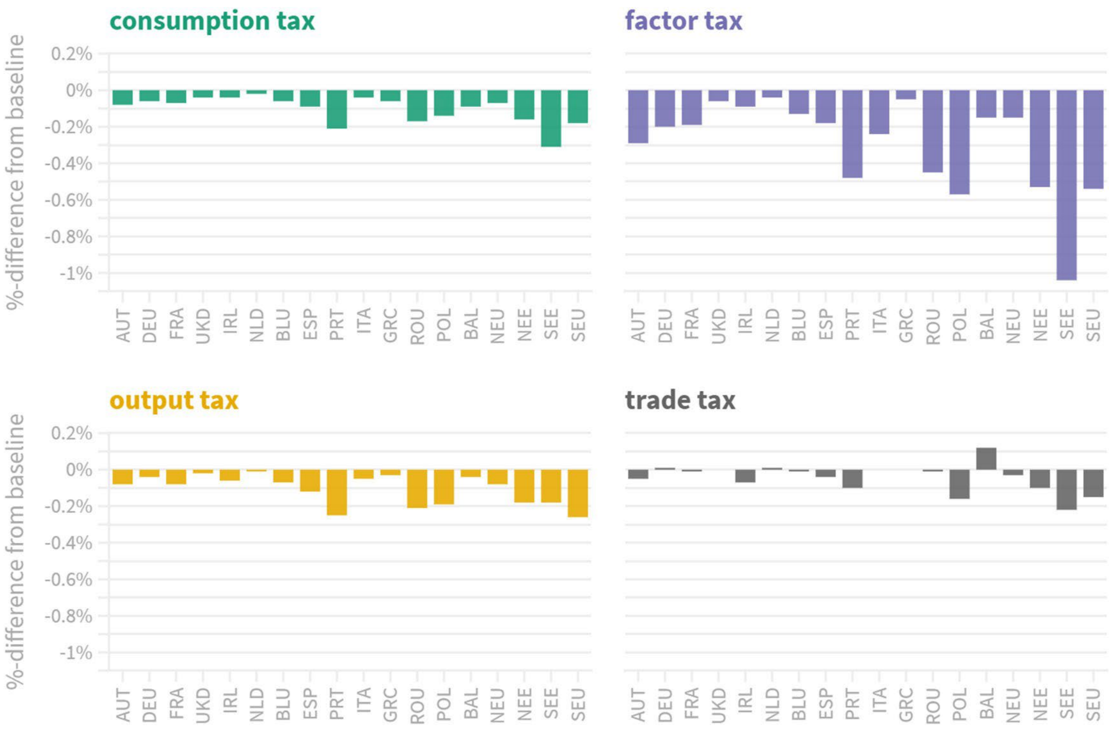

Figure 2.3.5: Change of tax income for consumption, factor, output and trade tax for EU regions; scenario combination: RCP8.5-SSP5 driven by the HadGEM2-ES GCM.

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Impacts in a climate change scenario with a change of insurance market systems to a public-private partnership and a solidarity market structure

Implications for insurance parameters

We modelled how a change of insurance system towards a public-private-partnership can enhance the capacity of insurance to cope with climate change in the DIFI model. As the PPP-system maintains a limited degree of risk cross-subsidization, premiums will rise or fall depending on the initial insurance system. For regions that maintained full cross-subsidization of risk in its solidarity system, such as France, Romania, Spain and Belgium (in BLU with Luxembourg), the model output shows an increase in premiums for high-risk areas after changing to a PPP. For regions that maintain voluntary insurance coverage in their initial system, such as Austria, Germany, Italy or the Netherlands, the change from fully- to partly risk-reflective premiums is projected to lead to a decline in premiums after the policy change. As a result of mandatory insurance uptake, the insurance penetration rate too rises significantly for these regions. Following the higher insurance uptake, more households are subjected to the incentive to apply risk-reduction measures, which results in higher household-level risk-reduction. In the case of France, there is also a significant increase in household-level risk-reduction, as the initial solidarity system did not provide premium discounts for risk-reduction measures.

Macroeconomic effects with a change of insurance markets to a public-private partnership and a solidarity market structure

The changed insurance parameters as output of the DIFI model are again implemented and analysed in the CGE model to understand the macroeconomic implications. Figure 2.3.6 displays the %-point difference for impacts on GDP, private and government welfare between the baseline insurance arrangements and each of the two scenarios: PPP and SOL. Hence, a positive value describes an improvement over the country's baseline insurance market system and a negative value a decline compared to the initial situation.

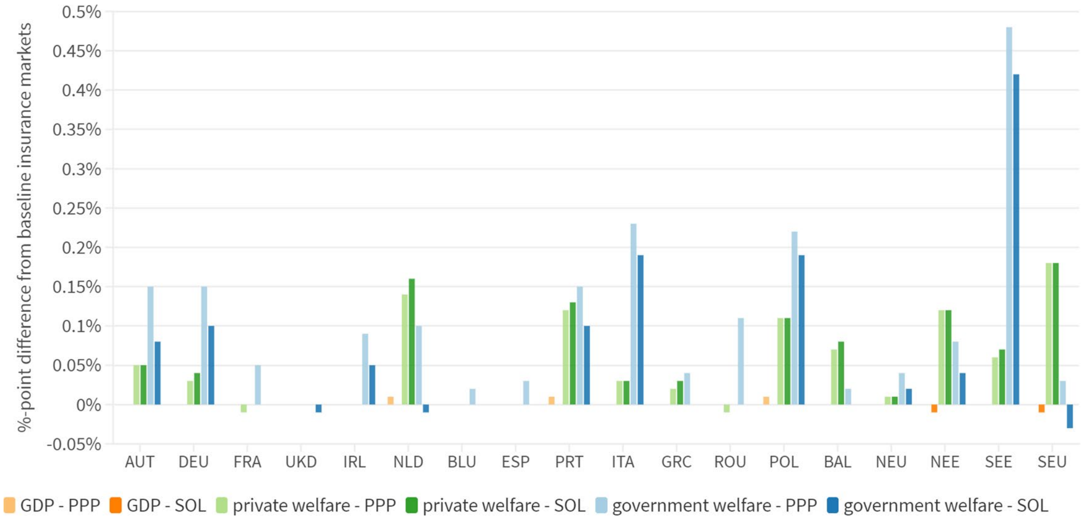

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Figure 2.3.6: Differences in macroeconomic outcomes based on the underlying insurance system for a change from the current system to a Public-Private Partnership (PPP) and a Solidarity market system (SOL) for European regions with modelled insurance market expressed in %-points; scenario combination RCP8.5-SSP5 driven by the HadGEM2-ES GCM.

What comes apparent immediately is that there are virtually no differences in GDP outcomes between the scenarios. A slight improvement can be observed for the Netherlands, Portugal and Poland when switching from a voluntary system to a PPP. Slight decreases are found for NEE and SEU. This indicates that as the CGE model depicts a closed system of flows and all markets are balanced, the redistribution of damages affects the question of who bears the burden of flood risk, but has a low impact on aggregate GDP. Hence, the differences in the welfare indicators are more pronounced. For those regions that maintain a voluntary system in the initial state, the switch to either of the two insurance scenarios constitutes an improvement for private and government welfare. However, whether the improvement towards the PPP or the SOL scenario dominates, varies between private and government welfare. While private welfare tends to be higher (or less negative when considering the impact) in the SOL system, government welfare is least affected in the PPP system. For example, Poland’s private welfare in both scenarios is higher than with the baseline insurance market system by 0.1%-points. Its government welfare is higher by 0.22%-points in the PPP system and by 0.19%-points in the SOL system. The strongly affected SEE region also experiences an improvement of 0.06%-points for private welfare and 0.48%-points for government welfare when switching to a PPP, and 0.07%-points and 0.42%-points when switching to a SOL system, respectively.

For those regions that in their initial insurance arrangement already maintain a solidarity system, the scenario where each EU country has a solidarity system does not imply any changes in the macroeconomic indicators. In contrast, the change towards a PPP system implies lower impacts on government welfare in all of these regions (France, BLU, Spain and Romania), but slightly higher impacts on private welfare in France and Romania. The only country with a PPP system in the baseline is worse off when introducing a solidarity system with only a slight decrease in government welfare mainly triggered by the cease of the reinsurance premium that is paid by private insurers to the government for cases of extreme damages.

Eventually, we analyse the EU-wide costs of the different insurance scenarios, where the baseline (BL) reflects the current arrangements and would thus describe climate impacts from riverine flooding on the EU level when current arrangements are maintained. These include the voluntary system for the majority of regions, but also the PPP for the UK and the solidarity system for France, BLU (Belgium and Luxembourg), Spain and Romania. The other two scenarios present a theoretical introduction of a uniform system in all EU countries, that is a PPP or a SOL system.

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In total, the change of insurance market systems have no effect on the GDP impact induced by flood damages in a climate change scenario (see Figure 2.3.7). For the private household, there is essentially no difference between the PPP and the SOL system with both of the systems being superior to the current insurance market systems. The main driver of this result is that there is no uncovered risk in the two systems involving risk-sharing mechanisms including the public household as one actor. As stated earlier, the negative consequence of the voluntary system, that is the enforced reduction of savings by the private household, which cannot be captured by the modelled macroeconomic effects, would further strengthen this result. While premiums and adaptation expenditures are significantly higher in the PPP than in the SOL, overall welfare costs are the same.

For the public household, current insurance market systems also induce the highest overall welfare costs. However, while there is no uncovered risk in both risk-sharing mechanism systems, government welfare is affected differently. The PPP induces lower welfare costs than the SOL system for two reasons: first, private insurers pay a reinsurance premium to the public household for covering potential excessive damages, which increases disposable income and thus counteracts the effect of direct climate impacts, and second, the risk reduction action carried out by private households reduce climate impacts in the first place with lower damages to the economy.

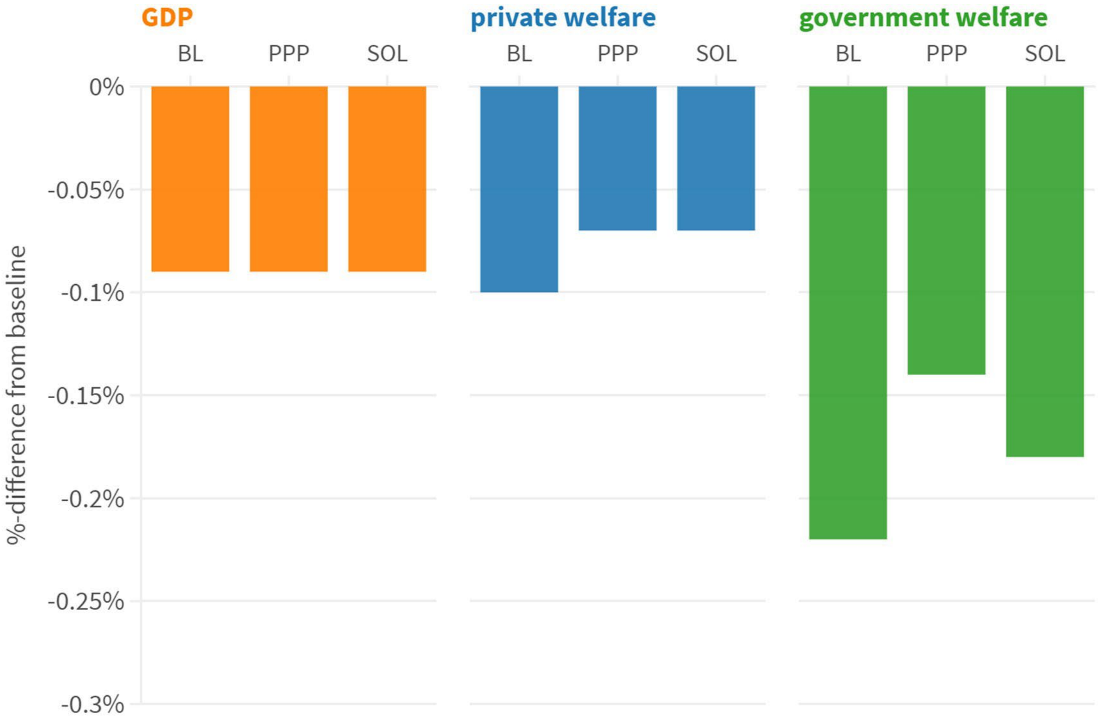

Figure 2.3.7: Differences in Europe-wide macroeconomic outcomes based on the underlying insurance system for a change from the current system to a Public-Private Partnership (PPP) and a Solidarity market system (SOL); scenario combination RCP8.5-SSP5 driven by the HadGEM2-ES GCM.

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Uncertainty range across RCP-SSP-GCM combinations for macroeconomic indicators with baseline insurance market systems and PPP and SOL

As flood damages by the mid of the century heavily depend on which emission scenario will be achieved and how society develops, as well as which global climate model is operated to project flood risk, we present the effects on macroeconomic indicators for a range of scenario combinations. Figure 2.3.8 shows GDP effects in panel (a), effects on private welfare in panel (b) and on public welfare in panel (c). The results support that, while a variation of emission and socioeconomic scenarios imply small variations in outcomes, overall patterns and qualitative findings as discussed above remain valid.

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Figure 2.3.8: (a) GDP, (b) private welfare and (c) public welfare effects for European regions with modelled insurance market for the current insurance market system (BL), a Public-Private Partnership (PPP) and a Solidarity market system (SOL) for the following scenario combinations: RCP2.6-SSP1, RCP2.6-SSP2, RCP4.5-SSP2 and RCP6.0-SSP2 with HadGEM2-ES and RCP8.5-SSP5 with HadGEM2-ES, IPSL-CM5A-LR, NorESM1-M, GFDL-ESM2M and MIROC-ESM.

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Discussion and conclusion

We assessed how a country's overall performance is affected by flood risk in 2050 under different insurance market systems, and how policy changes can improve this performance. For this we use stylized insurance market systems, which are based on current systems in EU countries and the UK. The purpose of this setup is not to most accurately predict the future situation, but rather to assess how certain policies can affect macroeconomic indicators and, thereby, contribute to the debate about adaptation strategies to climate change.

We find that flood damages in 2050 lead to lower GDP as well as lower private and public welfare in all EU regions. Results show GDP changes with a minimum of -0.03% for the UK and a maximum of -0.39% for South-Eastern EU (SEE, including Hungary and Bulgaria), private welfare ranging from -0.03% (UK) to -0.36% in Southern EU (SEU, including Croatia and Slovenia) and public welfare from -0.03% (UK) to -1.74% in SEE. While GDP losses are relatively insensitive towards the choice of insurance arrangement, alternative insurance market systems that involve a higher degree of risksharing among different actors can reduce overall macroeconomic costs by up to 0.48%-points (for government welfare in SEE). Public welfare is most sensitive to a change of the insurance arrangement as for example an increase in relief payments issued to the private household via transfers due to higher climate change damages reduces the government's disposable income. In contrast, the negative effect on private welfare can partly be absorbed by these transfers.

While several studies have argued that there is no one-size-fits-all solution for insurance markets (Hochrainer-Stigler and Lorant, 2018; Surminski et al., 2015), for EU regions a switch to a public-private partnership or a solidarity system is always beneficial as compared to the current insurance market system. For the EU in total, macroeconomic costs are lowest with a public-private partnership, followed by a solidarity system and with highest costs in the baseline scenario, where each country maintains current insurance mechanisms.

As results may seem small in size, we remind the reader that the insurance data only covers households placed in the 1/100 year flood plains in each region. While this is where most of the risk is located, we also abstract from behaviour in all remaining households. As the perceived risk is likely to be even lower in less risky areas, insurance uptake will also be even less there in a voluntary system. Thus, an event larger than a 1/100 year flood might lead to substantially larger losses than our model results suggest. We further want to emphasize that a large event such as a 1/100 year flood event in the Rhine basin or multiple flood events in several EU regions at the same time, are not unlikely, as river systems within a region may have simultaneously high discharge levels due to climatic similarities, and also a coastal storm surge can impact multiple river systems concurrently (Hendry et al., 2019). As a consequence, (inter)national relief

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funds such as the EU solidarity fund may bear a heavy burden when multiple countries require assistance simultaneously, as demonstrated by the Central European floods of 2002 (the year the EU Solidarity Fund was created) (Hochrainer et al., 2010).

In line with Hochrainer-Stigler and Lorant (2018) we suggest that risk due to natural disasters should be explicitly incorporated into government budgets (and planning processes) in order to enable potential partnerships on this scale. When substantial risk of disasters is not accounted for and coupled with weak fiscal conditions, substantial additional stress may be placed on the fiscal position during extreme events (Gurenko and Zakout, 2008). This may eventually lead to reduced fiscal space for public finances that fund other public investment projects. Thus to reduce fiscal vulnerability, ex ante risk management and financing measures can be taken, such as implementing risk prevention, offering state sponsored insurance to households or engaging in sovereign risk financing measures (Cummins and Mahul, 2008).

To summarize, maintaining macroeconomic performance within the EU and the UK requires adaptation in terms of physical risk-reduction measures, but also an adequate financial compensation mechanism for flood damage. In this study we showed that insurance policy changes that include uptake requirements, a public reinsurer, and limited risk-based pricing, can be effective to limit the macroeconomic impact of increasing flood risk due to climate and socio-economic change. While no engagement in the insurance activities may seem as the cheapest option at the first sight for policy-makers, additional expenditures arise when households are not sufficiently insured against damages and a social safety net is in place to prevent households from moving into poverty.

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○ 2.4 Policy effectiveness of insurance against natural hazards in Italy (CMCC)

Introduction

Italy is notoriously prone to natural hazards and disaster risk. Due to its peninsular and mountainous conformation, the country is susceptible to almost every type of hazard among which seismic and hydrological hazards are the most common. Among the 28 EU Member States (MSs), Italy has experienced the largest economic damage from natural hazards over 1980-2019, according to a recent analysis of the European Environmental Agency (EEA). The damage to tangible physical assets topped 147 billion Euro (in 2019 Euro value), on average ~ 3.67 billion Euro per year. This is about a third of the damage registered over the rest of the EU. The simulated expected annual damage (EAD) from floods in Italy has been estimated to around 800 million Euro (Feyen et al., 2012; Rojas et al., 2013, 2012), or higher if the spatial correlation between the flood risk across the major river basin in taken into account (Jongman et al., 2014). More recent Pan-European study has positioned the EAD higher (Alfieri et al., 2015). The insurance-industry commissioned study of natural hazard risks estimated annual average flood loss to residential properties in Italy to 230 million a year (compared to 2.6 billion Euro for earthquakes). Since 2002, Italy received post-disaster financial assistance amounting to 2.793 billion (in current prices) from the European Solidarity Fund (EUSF). This is equivalent to a half of the solidarity payments granted over the eighteen years of the Fund's existence (until November 2019).

The limited risk prevention and the legacy of uncontrolled urban expansion in the country contribute to amplify the risks and their impacts.

After examining insurance as a strategy for disaster financing, presenting current practices in selected EU countries and EU Initiatives related to residential insurance, this contribution focuses on the Italian case. It discusses its shortcomings and proposes some solutions to ….

Risk financing and insurance

A comprehensive strategy for disaster financing can moderate the impacts of natural hazard risks, speed up recovery and reconstruction, and harness knowledge and incentives for risk reduction. The OECD methodological guide defines risk financing as strategies and instruments used to manage the financial impact of disasters, ensuring adequate capacity to manage and mitigate the costs of disaster risk, thereby reducing the financial burden and economic costs of disasters and enabling rapid recovery in economic activity (OECD, 2012). A thorough understanding of risk exposure and risk bearing capacity, and institutional arrangements creating favourable regulatory and

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market infrastructure, are the major constituents of the comprehensive disaster financing strategy, along with the choice of optimal risk financing and transfer instruments.

Insurance is the most common form of financial protection against risk of contingent losses (Mysiak et al., 2017). The insured party or policyholder transfers the cost of potential loss to the insurer, in exchange for monetary compensation known as a premium. By acquiring the costs of contingent losses from many policyholders, the insurer absorbs, pools and diversifies the individual risks, making them predictable and manageable. When the loss occurs from specified contingencies under an insurance contract, the insurer indemnifies or compensates the insured party. The risk premium is a vehicle of risk allocation; an actuarial premium reflects the level of risk each policyholder contributes to the pool.

Not all risks are insurable or covered by insurers. Insurable risks are those that are quantifiable, in terms of both the probability of an event’s occurring and the extent of losses incurred, and for which premiums can be set for each policyholder or group of policyholders (Kunreuther and Michel-Kerjant, 2007). In addition, risk ambiguity, asymmetry of information (implying adverse selection and moral hazard), and correlation between losses influence the ability and willingness of insurers to underwrite risk and the level of premium sought (Charpentier, 2008; Jemli et al., 2010; Louaas and Goussebaile, 2016). If the latter are high, risks may be insurable but not affordable for low-income subjects, who may most benefit from insurance.

Hazard risks that have been amplified by climate change may make financial protection unaffordable for some people and risks uninsurable in certain places (see Kunreuther et al. (2011), (PRA, 2015), COACCH D3.4 (Bozen et al. 2020)).

Insurance is a financial service offering protection against the risks of contingent losses. But, directly or indirectly, it also serves other purposes. By facilitating prompt post-disaster recovery, insurance helps to contain the economic and social impacts of disasters. Beyond that, insurance serves public interests by promoting social protection and public welfare. Insurance makes it possible, for example, for individuals to get mortgage loans or compensation for injuries without going to court (Talesh, 2012). Insurance can also promote numerous economic activities in the higher risk/return market spectrum (Grant, 2012), thus contributing to higher productivity and innovation. And it can incentivise behaviour change and individual risk prevention, as shown in the next sub-section.

A variety of insurance schemes exists, depending on type of risk and protected asset (property, business assets and interruption, liability, sovereign risk, etc.). Natural hazard insurance is either an extension of property insurance (Bräuninger et al., 2011) or a stand-alone agricultural (crop yield, revenue, income) and energy insurance. Sovereign insurance (Mahul and Ghesquiere, 2007) covers costs associated with damage to infrastructure and relief expenditure. In general, insurance indemnity is proportionate

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to the loss incurred. Parametric or index insurance schemes employ other, more easily measurable indices (for example rainfall, yields, vegetation index) for determining pay-offs (Collier et al., 2009; Hazell et al., 2010; IFAD and WFP, 2011).

Other financial instruments can be based on debt, equity or their combination. Debt instruments such as loans or bonds are assets that yield the lender an interest. Loans from the banks or other financial institutions like mortgage. Bonds are fixed income instruments involving loans made by an investor (or creditors) to a borrower such as companies or governments to finance projects. Bond specifies the end date when the principal of the loan is due to be paid and includes the terms for interest payments. Green bonds are bonds that have positive environmental and/or climate benefits. Catastrophe or CAT bonds are instruments used to obtain a financial coverage to climate-related events. They are defined as fully collateralized instruments that pay off on the occurrence of a defined catastrophic event (Cummins, 2008). If the event occurs, investors will lose the capital invested in part or at all and the issuer will use that money to recover from the damage. In a more detailed definition, CAT bonds are securities that pay regular coupons to investors unless a predetermined event occurs, leading to a full or partial loss of capital (Braun, 2016). Resilient impact bond is a bond through which an investor is remunerated based on how well resilient measures are implemented, according to pre-defined performance indices (Vaijhala and Rhodes, 2018). It aims to promote resilience and finance infrastructure reinforcement interventions, combining an index that measures the resilience of an infrastructure into a financial tool.

Examples of insurance instruments in some countries

In Europe, the most longstanding insurance-related public-private partnership are represented by the extraordinary risks insurance scheme of Spain’s Insurance Compensation Consortium (Consorcio de Compensación de Seguros - CCS). Instituted in 1954 after its provisional creation in 1941, the CCS is an independent public company attached to the Ministry of Economics, Industry and Competitiveness but with separate accounts and a certain degree of entrepreneurial freedom (CCS, 2016). The extraordinary hazards covered are well defined in the statutes and include floods (before 1986 conditional on declared catastrophe zone); cyclones, tornadoes and windstorms (with gusts exceeding 120 km/h); earthquakes; tidal waves; volcanic eruptions; meteor strikes; and other hazards such as acts of terrorism and civil unrest. Spain counts additionally with a comprehensive combined agricultural insurance, managed by a pool of private companies in which CCS participates both as a co-insurer and as a reinsurer. The bulk of compensations referred to floods and windstorms (Espejo Gil, 2016). The scheme is financed by compulsory surcharge on designated insurance policies. Insurance policies covering property damage (with some exceptions), business interruption and personal life and accident. The flat rate surcharge is based on the total insured value and varies only across the type of underlying insurance policies. For example for dwellings and office building the surcharge amounts to 0.008 per thousand. The same rate applies without differentiation for any degree of exposure and any risk

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across the entire country, as it is calculated considering all claims and risks covered as a whole. Deductibles are applied to commercial policyholders but not to households (ibid.). Risk underwriting is the task of private insurers, and the extraordinary risk cover is entirely transferred to CCS. In exchange, the insurers retain 5 % of the collected surcharges to cover administrative costs. Claims are managed and indemnified by CCS. The fact that the scheme has very low administrative costs (less than 10 % of the collected surcharges including the costs of claim processing) is an argument in favour of this arrangement (von Ungern-Sternberg, 2004). Half of the CCS Board of Administrators is composed of chief executive officers from Spanish insurance companies and the other half of senior officials of the public sector. All decisions affecting CCS or the Extraordinary Risk Coverage System emanate from the board, setting another example of PPPs, which is also a flexible mechanism to easily introduce modifications to the system.

France introduced the ‘Catastrophes naturelles’ (CatNat) insurance regime back in 1982 in the aftermath of the devastating Saône, Rhone and southwest France floods (CCS, 2008; Magnan, 1995). It is based on a mandatory extension of insurance policies against fire and damage to property (theft, water damage, etc.) and land vehicles, to protect also against damage caused by extreme natural hazard events deemed uninsurable. A defining characteristic of the CatNat regime is that the exceptional character of the natural hazard events, serving as a trigger for damage compensation, has to be sanctioned by an interministerial decree. What qualifies as natural disaster is not exactly specified by statutes and is indeed sanctioned case by case. The CatNat system usually applies to floods, landslides, subsidence, droughts, avalanches, earthquakes and tidal waves. CatNat exemplifies a system in which policyholders cannot exclude the natural hazard coverage, and the insurers have to supply it (Grislain-Letrémy et al., 2012). The additional premiums (or surcharges) are set by the government as uniform percentage rates of the underlying property insurance premium without any regional differentiation, equal for all risks covered and any degree of risk exposure. The government also determines the level of deductibles that are compulsory even if the underlying (base) policies do not envisage them. The deductibles serve as an incentive for risk prevention: the policyholders in districts without a risk prevention plan (Plans de Prévention des Risques - PPR) have to accept higher deductibles when exceptional events of the same hazard types occur consecutively (von Ungern-Sternberg, 2004). In addition, a levy on the CatNat premiums flows into aFund for the Prevention of Major Natural Hazards (Fonds de Prévention des Risques Naturels Majeurs - FPRNM), which finances prevention measures. Private insurers underwrite the risk, collect premiums and process the claims. Except for the premium rates and deductibles, the natural disaster cover follows the terms and conditions of the underlying insurance policy. The insurers may choose to reinsure the underwritten risks by a Central Re-insurance Company (Caisse Centrale de Réassurance - CCR), initially a public entity of commercial nature and later turned into a state-owned limited company. The CCR offers two types of complementary and inseparable reinsurance contracts: (i) quota-sharing contracts under which the CCR accepts a share of the risk in exchange for a share of the collected

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premiums; and (ii) stoploss contracts under which the CCR compensates the loss that exceeds the insurer's annual premium income by a certain factor (OECD, 2014). The CCR holds a dominant position in the reinsurance market in France (Grislain-Letrémy et al., 2012). In 2015 the French Insurance Federation (Fédération Française de l'Assurance - FFA), estimated that by 2040 the human induced climate change may increase the disaster losses by 90 % (EUR 44 billion) compared to losses over the past 25-year-long period (FFA, 2016a). To improve the sustainability and viability of the CatNat regime, the FFA made several suggestions about how to make DRR an integral part of the regime. Among other things, the FFA recommended that the insurers should be able to define the level of deductibles for major policyholders (with insured value beyond EUR 50 million)(FFA, 2016b).

Flood Reinsurance Scheme (FR Scheme) in the UK as an example of a public-private reinsurance mechanism for flood components of housing policies. Private flood risk insurance in the UK has a long tradition and coverage of residential properties is among the highest in Europe (Maccaferri et al., 2012). Housing insurance typically covers a portfolio of risks in addition to floods and is compulsory for securing mortgage loans. Public-private cooperation in the flood insurance sector started in the 1960s and gradually evolved into a partnership entailing tangible commitments on both the public and private ends (Penning-Rowsell et al., 2014; Ball, Werritty, & Geddes, 2013; Lamond, Proverbs, & Hammond, 2009; E. Penning-Rowsell & Priest, 2015). Statements of Principles, the latest of a series of informal agreements between the UK Government and the Association of British Insurers (Crick et al., 2013; Horn and McShane, 2013; Surminski and Eldridge, 2015; Surminski et al. 2014), was replaced by the FR Scheme.

The FR Scheme had been designed as a publicly accountable but privately owned and managed, non-profit service organisation. The ownership and management of the Scheme is entirely in the hands of the insurance industry, with a limited Government's role. The commercial insurers are free to choose whether to reinsure the written market risk or cede the flood-risk component of housing policies to the Scheme at predetermined, capped prices. In the latter case, any and all damage claims are paid by the Scheme and the primary insurers continue acting as a broker. Under the FR Scheme, the premiums are capped at a level that is higher on average than what was paid previously, but lower than prices otherwise charged on the free market (Diacon, 2013). The capped prices are specified by regulation (FR Regulation, 2016), annually updated by the Consumer Price Index, and revised every 5 years.

The FR Scheme is funded by an annual statutory levee set at 180 million GBP for the first 5-year period, which is imposed on all home insurers operating in the UK. The total amount of the primary levee was decided as an equivalent level of current cross-subsidy which amounts to an estimated 10.5 GBP per household. The FR Scheme Administrator can raise supplementary (top-up) levees or contributions in cases where it does not have sufficient resources to meet its non-reinsured claims.

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EU Initiatives related to residential insurance

In 2013, and as part of the EU Climate Adaptation Strategy package (EC, 2013a), the European Commission (EC) launched a broad consultation about what EU action could be appropriate for improving the performance of insurance markets (EC, 2013b). The responses cautioned against uniformizing the regulation on natural hazard insurance across the EU (EC, 2014). Both the uneven-distribution of hazard risk and the diversity of the economic standing and other requirements of customers have been brought up as reasons against an EU intervention (HM Treasury, 2013). Consequently, uniformized regulations could harm innovation and competition in insurance products. The Dutch government emphasized that a concerted EU action in this policy area was neither warranted nor in line with the subsidiarity principle of EU governance (NL, 2013). The European Parliament (EP) expressed a similar opinion (EP, 2014) while underlining that flexible markets should operate in a non-mandatory framework and that no one-size-solution-fits-all would serve the magnitude of different risk and economic conditions in Europe. The 2018 evaluation of the Strategy acknowledged that not all hurdles for public-private cooperation may have been overcome (EC, 2018). The added value of EU action should enable cooperation between governments and insurers, raise awareness about the coverage gap and about the need for governments to integrate insurance in the management of all climate risk. Therefore, insurance remains as a priority of the revised 2021 EU Adaptation Strategy (EC, 2021).

Residential insurance against natural hazards in Italy

Notwithstanding the high exposure to natural hazards, property insurance coverage in Italy is low, except for explosion and fire, not necessary of natural origins, which is a mandatory requirement for obtaining mortgage loans. The system of state *compensations* of disaster losses, which does not constitute a *duty-to-compensate* but connotes a long-establish customary practice, impedes private insurance markets. Over the past decades there have been numerous, so far fruitless attempts to give a boost to a private insurance market and relieve the notoriously ailing public finances. Most of these proposals embraced some type of coercive *public-private partnership* (PPP) and risk sharing. Typically, the schemes that were put forward have imposed duty on homeowner to underwrite disaster insurance or to extend existing policy to natural hazard risks. Often the same and only slightly changed proposals were submitted under different, quickly succeeding legislatures that characterised Italy's political system in the 1990s.

The early legislative proposal in the upper house of the parliament, presented by Sen. Cesare Golfari (Christian democrat), dates back to 1993 (Golfari et al., 1993). It envisaged creating a civil protection fund financed by a supplementary municipal real property tax[5] (RPT), and divided into four budgetary lines, including *emergency response fund* (ERF);

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[5] The municipal real estate tax (in Italian *imposta comunale sugli immobili*, ICI) was instituted in 1992 and was replaced in 2012 by local property tax (*imposta municipal unica*, IMU)

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business recovery fund (BRF); *public property fund* (PPF); and *private property fund* (PRF). Around two thirds of the envisaged annual revenues, totalling to 1.7 billion in 2015 prices, was meant for backing the PRF. The remainder (around 800 million Euro) was to be divided between the other lines: ERF (400 million) and the BRF and PPF (200 million each). PRF and BRF were meant for subsidised reconstruction loans. The building insurance represented by PRF was mandatory for all *private* and *public* buildings for which the RPT was applicable.

The proposed insurance scheme envisaged a mandatory participation of all insurance undertakings operating in Italy, united in a consortium, and dividing the duty according to their market shares in loss insurance branch. The role of the insurers' consortium was slashed to passive engagement and administrative management. Local municipalities (or better, municipal civil protection committees presided by mayors) were to act as intermediaries authorised to underwrite insurance contract for all building owners within their jurisdictions; to enact the law; and to collect the risk premiums. The Government was to regulate insurance prices and classify the zones of risk, and the Parliament was purported to supervise the scheme. The insurance policies were designed to include deductible equivalent to 15% of the insured value. A small part of the PRF (around 250 million Euro) was to be set aside as state-managed reserves for the case the total indemnities in a given year exceeded 11.4 billion Euro, essentially an upper bound of the insurers' liability in any single year. The insurers' consortium was compelled to seek reinsurance at the international market.

The same legislative bill was submitted by Rep. Maura Camoirano (Social democrat) to the lower chamber of the Parliament (Chamber of Deputies) in the successive (12th) legislature, in June 1994 (Camoirano et al., 1994), and re-proposed with modification in the May 1996 in the next following (13th) legislature (Camoirano and Lorenzetti, 1996). The modified proposal maintained the same principles, including the nominal value of RPT. However, the real value of the tax revenues dropped in meantime by 13% as a result of the high inflation (5% annually on average) between 1993 and 1996. One noteworthy modification was the elimination of the deductibles and the re-distribution of PRF, now worth 1.46 billion Euro (in 2015 value). Some 290 million Euro were to be managed by the Government itself to compensate damage not exceeding 20% of the insured value, whereas the rest (1.17 billion Euro) was to be transferred to the insurers' consortium. The maximum annual exposure of the latter was reduced to 9.3 billion. Losses exceeding this limit were again to be compensated by the state.

In June 1998, Rep. Francesco Aloisio (Social democrat) submitted another legislative proposal (Aloisio, 1998) to the lower house, which was only few weeks later reiterated, with minor modifications, by Rep. Camoirano, Lorenzetti and other deputies, including Aloisio (Camoirano et al., 1998). These legislative bills were examined together with the proposal from at that time centre-right opposition, submitted by Rep. Claudio Scajola (Forza Italia, centre-right wing party) (Scajola et al., 1999). In 2011, the Scajola's legislative proposal has been resubmitted in the 14th legislature in the upper house of

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the parliament by Sen. Luigi Manfredi of the centre-right government coalition party, with no substantial change.

The proposals by Aloisio and Camoirano et al. included, only for residential buildings, a mandatory extension of the existing explosion and fire (E&F) policies to cover natural hazards. Rather than delimiting the scheme in detail, both proposals merely specified main principles of the intended PPP, and mandated the government with the task of tabling a legislative decree regulating the details. The residential property insurance was but a part of a far-reaching reform putting up disaster prevention at the centre stage. Part of the reform was improving risk assessment, a better inter-institutional coordination, and setting up a fund for disaster risk reduction equipped with budgetary resources no more needed for private damage compensation. Initially, the Fund was to be equipped with 700 million Euro. Properties situated in very high-risk zones, delimited by the government, were exempted from the insurance obligation and the risk premiums paid directly from the Fund. The same applied for buildings with high cultural value and low-income households. The mandatory insurance extension included a deductible of 10% which however could have been covered, partially or entirely, by public funds. The insurance companies were left free to determine risk premiums but within the risk territorial classification designated by the government. A lower value-added-tax was applicable on the insurance contracts and the risk premiums paid were deducible from the income tax. The role of state as the insurer of last instance would have remained in place and the indemnities exceeding in a single year 2.1 billion Euro were compensated from public funds.

The proposals of Scajola et al. and later Manfredi et al. mandated government to table an insurance-based PPP and consolidated the practice of state compensation of disaster losses, including also the damage to the content in function of the household income.

The governments themselves, from both political flanks, have attempted to institute mandatory insurance in 1998, 2003, 2005 and 2012. These attempts typically entailed a mandatory extension of the E&F policies consistently with the proposals of Aloisio and Camoirano et al. The legislative proposal presented by at that time treasury minister Carlo Azeglio Campi (Ciampi et al., 1999), later the same year elected as the president of the state, addressed among others also the loss compensation for non-insured damage (limited to 30-60% of the total loss experienced), except for low-income households for which the compensation of the entire loss was consented; revenue neutral tax reduction; establishment of a guarantee fund; and the cooperation between the insurers.

The Italian Antitrust Authority (IAA) issued two negative opinions on the government's plan, in 1999 and in 2003. The Authority vented reservations with respect to these plans. IAA noted that the mandatory extension of E&F policies needlessly distorts market competition, firstly by stimulating unwarranted agreements between insurance undertakings; and secondly, by bundling two products out of whom only one necessitates public intervention. The Authority feared that the E&F insurance market

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may become unduly influenced by selection bias – only those who voluntarily subscribed E&F policies would be obliged to underwrite natural hazard insurance regardless the hazard exposure of their properties – and that the regulated risk pricing of latter market segment may lead to higher market prices of the former segment. Besides, the allotment of the regulated and subsidized natural hazard insurance policies may lead to unjustified anti-competitive agreements between insurers, hence comprising effectiveness of the scheme. The IAA noticed that some cooperation among insurers would be necessary for both, a better understanding of risk and capacity to re-insure against excessive obligations from insurance claims. But this cooperation should be limited so as to minimize the eventual market distortion. The Authority also noted that the envisioned transfer of risk away in competitive markets was at odds with the solidarity principle entailed in the subsidized or sponsored insurance of low-income households. Theformer demands preservation of undistorted competition while the latter was better attainable outside the market mechanisms, ideally by means of general taxation.

The more recent legislative proposals examined by the Italian parliament, the 17th legislature period, included the proposal of by Rep. Giulio Cesare Sottanelli (Liberal Democrat) (Sottanelli et al., 2013) and Sen. Enzo Fasano (centre-right wing party) (Fasano et al., 2013). The former proposal was submitted to the lower house and the latter to the upper house of the Parliament.

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Table 2.4.1: Summary of the key characteristics of the proposed insurance schemes

Feature of the proposed PPPs	**Characteristics of the schemes**
Mandatory insurance underwriting	Low penetration in property damage segment for damage caused by natural hazards has been addressed by most legislative proposals through mandatory underwriting of insurance and/or, more frequently, through mandatory extension of existing fire and explosion policies. The 1993 Golfari proposal bundled the risk premiums to the real property tax.
Voluntary insurance underwriting	Voluntary insurance underwriting is dissuaded by existing practice of state compensation for which, however no legal obligation exists. The various proposed PPP were meant to reform the current ineffective and costly compensation practice.
Mandatory insurance provision sides the companies	Insurers are obliged to introduce or extend their portfolio of insurance products to cover natural hazard risk. The obligation ranged from a compulsory participation all insurers to compulsory bundling of insurance products. Cooperation between insurers was either mandated or encouraged. The pursued scope of the cooperation entailed risk assessment and transfer, including reinsurance of a part of the accepted risk.
State guarantee	The envisaged role of state included risk zoning, regulation of the risk pricing and back-stop guarantee for total annual claims exceeding a given threshold. The latter varied between around 11 and 2 billion Euro in 2015 Euro values, depending on the various proposals.
Consolidation of state compensation regime	The existing compensation regime was to stop entirely or was to be preserved in limited form for uninsured properties and low-income households. The compensation was either limited to structural damage or extended, in limited form, to damaged content.
Fiscal incentives rateand tax reduction	The insurance premiums were to be taxed with a lower than usual and were deductible from income tax up to certain level.

The Sottanelli's proposal is consistent with the earlier schemes but is more articulated in the way the risk is layered, however, without enumerating the thresholds between the various risk transfer layers. The proposal is said to be backed by the Italian Association of Insurers; the Italian Banking Association[6]; the Bank of Italy; and the real estate owners' association. According to the proposal, the insurance coverage is mandatory for all residential buildings, and subject to a unified risk pricing based on the average construction costs, differentiated by category of buildings. The real property

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[6] ANIA, Associazione Nazionale fra le Imprese Assicuratrici; ABI, Associazione bancaria italiana,

owners may opt for various indemnity levels, but the system envisages a not-quantified deductible for frequent minor losses. All insurers active in Italy are to become part of the mandatory insurers' consortium and obliged to provide insurance coverage for natural hazards that include quakes, volcano eruptions, landslides, floods, and extreme winds, hails and snows. As a second risk transfer layer, the insurers' consortium will seek to reinsure part of the assumed risk at international reinsurance market. The management of the claims is organised by third parties appointed for this scope by the government. The claims are conditional to the declared state of emergency (SoE) by the government or the Civil Protection Department. The third layer of risk transfer is comprised by mandatory acquisition of cat-bonds by all banking institutions active in Italy. Finally, the system foresees the back-stop guarantee by the state for losses exceeding the carrying capacity of the previous three layers.

The Fasano proposals departures from the stream of previous proposals by not only imposing a mandatory insurance for all public and private buildings; the mandatory insurance serves to collect revenue to retrofit the buildings and increase their 'security'. The proposal quantifies the average risk premium as amounting to 100 Euro per year. This amount would be doubled, and the additional resources transferred into a National Fund for security and energy efficiency of buildings for financing ex-ante risk reduction and improved energy efficiency of the buildings.

Under the current XVIII legislative period (since March 2018), a new proposal has been submitted by Rep. Rostan (independent) in June 2019 (Rostan, 2019). Similar to previous proposals, the schemes is articulated in three layers: private insurers or (mandatory) insurance consortium stipulate the policy with households and may choose to transfer part of the risk the reinsurance companies or consortia. State guarantee is organised through a dedicated fund created and managed by CONSAP (*Concessionaria Servizi Assicurativi Pubblici*, National Insurance General Agent[7]), to which the primary insurers transfer 5% of the collected premiums. The Guarantee Fund can only be activated after a state of emergency has been declared, and a roster of independent experts is established for a quick administration of the claims. The members of the proposed national insurance partnership include the Civil Protection Agency, the National Research Council, the Institute for the Supervision of Insurance, CONSAP and the insurers/re-insurers operating in Italy. The insurance against extreme natura hazard events is mandatory for all residential units. The insurers can introduce deductibles according to the risk levels the building are exposed to, but the deductibles cannot exceed 10% of the insured value of the property and should be accompanied nu a discount on risk premiums of at least 15%. The premiums are exempted of any taxes and can be detracted from the general income tax.

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[7] CONSAP is a joint-stock company, created in 1993 by spin-off from the National Insurance Institute, and is entirely owned by the Ministry of Economy and Finance, was formed in 1993. CONSAP manages various guarantee and solidarity funds and various services.

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Noteworthy is a study conducted by the Institute for the Supervision of Insurance (*Istituto per la Vigilanza sulle Assicurazioni*, IVASS) (Cesari and D'Aurizio, 2019). The study analysed two hazards - earthquakes and floods - and estimated insurance premiums for the case in which all residential buildings would buy a cover. For earthquakes, an average premium of 130 Euro per year would make it possible to compensate the entire entity of damage to buildings constructed using less resistant, traditional standards. Introducing a deductible of 6% would reduce the premium by 40% according to the authors. Retrofitting the building to modern, more resistant standards would reduce the premiums by 30%. For floods, the estimated premium is 4-6 Euro on average, and up to 20 Euro for areas exposed to higher risk levels. Average premiums in case of combined cover of earthquakes and floods would amount to 100 Euro, assuming a modest levels of deductibles. The study suggested two ways of reinforcing the insurance cover: The first does not introduce an obligation to buy insurance but invest in public awareness and fiscal incentives, and couples the insurance with the mortgage contracts. The second foresees the mandatory insurance cover accompanied by fiscal incentives, risk awareness campaign and reinforcing the sense of social/collective responsibility.

Discussion and conclusions

The review in the previous subsections showed that actuarial risk pricing has never been envisaged neither in short- nor in long term. The schemes take for granted that actuarial risk pricing is either not socially equitable or not viable. High number of underwriters reduces risk premiums for all and underpins a type of that is striven for solidarity. Up to date there has been no or limited public debate and consultation about what solidarity principles should the insurance-based PPP be based on. This is important insofar the current hazard exposure is at least to some extent a result of decades-long unsustainable land management and spatial planning practices. As a result, one may argue that in the current situation the collective accountability hold sway over individual responsibility and risk-careless choices.

The currently established practise relies on general tax revenues in which the income taxes have the largest share. The compensation regime exemplifies a solidarity that entails transfer of wealth from high- to low-income households regardless the hazard exposure or risk reduction undertaken to limit the damage. From the stream of legislative proposals described earlier one may infer a critical attitude towards buildings constructed in high hazard-prone areas, without building permission even if later legalised. In the case of mandatory underwriting of insurance or a mandatory extension of existing policies the solidarity towards those who do not possess insurance fades.

The *tripartite* mandatory nature of the Sottanelli scheme that obliges property owners to underwrite insurance contracts, insurers to become part of the pool, and credit institutions to buy cat-bonds, does not abide with the rules of free internal market and disincentivize individual risk-sensitive behaviour. It embraces entirely solidarity and disowns individual or collective responsibility for risk. In other words, the scheme does

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not put an end to the state *paternalism*, it only choses another form. Up to now the non-enforceable compensation of disaster losses counted on public funds and therefore on all taxpayers; the new scheme does the same but shifts the burden to residential house owners. Only to limited extent, as the risk premiums paid are deducible from the due amount of income tax, and cat-bond yields and the losses associated with the highest risk-tier are to be shouldered by public funds. But as a quantifiable and legally enforceable liability, the ensuing risks will add to already high public debt. Adding to that, the real estate property owners are already paying for flood risk protection via land-drainage charges. This means that they will be asked to pay for the risk protection twice which will likely be legally contentious.

The obligatory underwriting constitutes *state resource* according to the state aid regulation, not dissimilar from a tax, and so does the tax reimbursement or reduction. The insurance undertakings are beneficiaries of the state aid but because all of them, without exemptions, are part of the insurance consortium managing the scheme, a selective preferential treatment can be dismissed. New insurers who embark on business in Italy will have to enter the consortium, meaning the distribution of individual quotas will need to be reshaped. This may potentially lead to high transaction costs of the scheme. Notably, it is likely that the mandatory acquisition of the cat-bonds will be seen as comprising a state resource as well. With other words, the losses in the third tier of the scheme aren’t but selective taxes imposed on credit institutes to advantage the insurers’ consortium.

The abridged risk premiums determined according to sole typology of the buildings and the chosen level of protection does not encourage individual risk reduction. In contrary, the habitability in high risk-prone areas will be subsidised through buyers of insurance in places in which the risk poses no or very little concern. Indirectly, the unsustainable and risk-negligent development practices in the past will be rewarded, and therefore resumed, rather than made to pay up for faulty choices. In the current form, the scheme is not detailed sufficiently to realize to what extent it coins additional burden on people at-risk-of-social-exclusion or exacerbates the existing inequalities.

Finally, the proposed scheme cares little about the changing magnitude of risk from extreme weather and climate-related events, driven by societal and environmental changes, including climate change, soils sealing, land use conversion, and demographic transformation. These drivers may lead to a substantial increase of *annual average loss* (AAL) in medium-long terms that will either lead to higher risk premiums for all house owners, or a more frequent transfers of risk to the third or the fourth risk triers.

A sensible reform would first offer a long-term vision, based on and entirely informed by an inclusive public debate. Such as vision should identify a reasonable level of solidarity that does not inhibit individual risk reduction behaviour. The actuarial risk pricing is neither socially fair nor viable in short term, but this does not mean it should not be striven for in medium- to long term. A smooth transition towards a reasonable risk pricing over a period of thirty years or longer may send a signal to real estate market

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that delivers tangible outcomes gradually. Second, the risk and financial burden should be equally split among public and private entities engaged voluntarily in a partnership. The partnership itself should be based on sound risk assessment and every house owner or lessee should find it easy to access the information about the risk exposure of the owned or leased property. Third, the scheme should differentiate between levels of hazard exposure and, to the extent possible, pool the risk among the property owners within the same or similar categories of risk. Fourth, any duplicity between existing financial and economic instruments, including payments for water services or indivisible municipal services (the costs of which is recovered by property taxes or charges) and the envisaged scheme should be avoided. In the case of flood risk this may result in risk premium discounts proportionally to the amount of tax or service charges already paid. (Sudmeier-Rieux et al., 2021).

A sensible way forward may be to entrust the development of the public-private insurance scheme to a citizen assembly. Citizen assemblies can help unlock more effective action and help solving intractable issues. A citizens' assembly (Aichholzer and Strauß, 2016; Bain and Bongiorno, 2020; Devaney et al., 2020b, 2020a; Howarth et al., 2020; McGovern and Thorne, 2020; Muradova et al., 2020; Niessen, 2019) is a group of people brought together to learn about and discuss issues and reach conclusions about what should be done. The citizens are chosen randomly, based on demographic criteria and attitudes. Participants interact with a range of experts, practitioners, stakeholders and campaigners. Climate Citizens' Assemblies were held in Ireland, France and UK (Mellier-Wilson, C.; Toy, 2020; Smith, 2020; Wilson, C., & Mellier, 2020). The latter gather 108 people to make recommendations for how the UK can reach its net zero target by 2050 (Climate Assembly UK, 2020).

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[1] Note that this is only true given the modelling choice of not allowing to incur public debts, Parrado et al. (2020) investigate the effects on public budgets allowing for additional debt.

○ 2.5 Policy effectiveness in infrastructure, built environment, and transport for investments (lead: GCF)

This case will assess alternative adaptation policies on coastal areas, such as protection, flood-proofing buildings and coastal retreat, and riverine floods. Based on the improved assessment of financial costs and economic losses caused by fluvial floods, our study will inform an on-going public dialog on a proposed residential flood

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insurance scheme in Italy intended to increase insurance penetration and guarantee a strong financial backing in view of uncertain tail distributions of risk. Developed in collaboration with Italian Association of Insurers and the Prime Minister Office's flood coordination unit, our study will analyse how effective and efficient are the legislative proposals currently under parliamentary review.

This section assesses alternative adaptation policies on coastal areas, such as protection, flood-proofing buildings and coastal retreat, and riverine floods.

2.5.1 Coastal Flooding

The effectiveness of coastal adaptation has been assessed mainly from an economic perspective. Using a benefit-cost analysis approach, Lincke and Hinkel (2018) conclude that 13 percent of the world's coast by length is worth protecting against SLR over the 21st century irrespective of the uncertainties, while 65 percent of the world's coast by length is never worth protecting. In terms of assets, the 13 percent of coast contains 96 percent of assets. Within COACCH this analysis was extended and it has been shown that if coastal retreat is taken into account still about 3 percent of the global coastline is worth protecting against SLR over the 21st century irrespective of the uncertainties, covering 78 percent of global coastal population and 92 percent of global coastal floodplain assets (Lincke and Hinkel, 2020). Recently, local studies discussed the effectiveness of other adaptation measures for the building stock, i.e.infrastructure elevation and flood proofing (Han and Mozumder, 2021).

Here, we analyse the effectiveness of additional adaptation measures for coastal areas. In addition to the adaptation measures modelled in the earlier deliverable D2.3 (Lincke et al, 2018) and deliverable D3.3 (Botzen et al., 2020) - protection with hard infrastructure and coastal retreat with associated migration - we model two more adaptation options: flood proofing of infrastructure and elevation of infrastructure. These two options will be combined with the adaptation scenarios used in D2.3 and D3.3 - building dikes and retreating from the coast. Flood proofing of infrastructure, elevation of infrastructure and coastal retreat will be considered as secondary adaptation options. That means, the stylized adaptation rule used in D2.3 will be used to decide whether a coastal segment is protected with dikes or not. Afterwards we assume that one of four additional measures will be applied to unprotected areas:

1. No additional measures
2. Coastal retreat as described in deliverable D3.3
3. Flood proofing of infrastructure is described below
4. Elevating infrastructure as described below.

The cost and effects of these four adaptation options will be analysed.

Flood proofing of infrastructure

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There are different methods of flood proofing infrastructure - here we only consider dry proofing. Dry flood-proofing techniques are designed to prevent floodwater from entering a building. Measures include for instance the protection of doors and other openings with permanent or removable flood shields by sealing walls with waterproof coatings, impermeable membranes or supplemental layers of masonry or concrete.
The DIVA model is used for the analysis to represent all capital in the form of a stylized capital stock, which means that there is only one kind of capital. Flood damages to this capital stock are computed by the means of a depth-damage function. Thus, we model flood proofing by a modification of the depth damage function: while the damage function of infrastructure that is not flood proofed starts at 0.0 meter flood depth and causes damage from the first centimetre of flooding (black line in the Figure 2.5.1), flood proofed infrastructure does not suffer any damage when the flood depth is below the flood proofing height. Figure 2.5.1 illustrates this for flood proofing heights of 0.5m and 1.0m. In our model of flood proofing a flood depth above the flood proof height leads to the same damage as unproofed infrastructure.

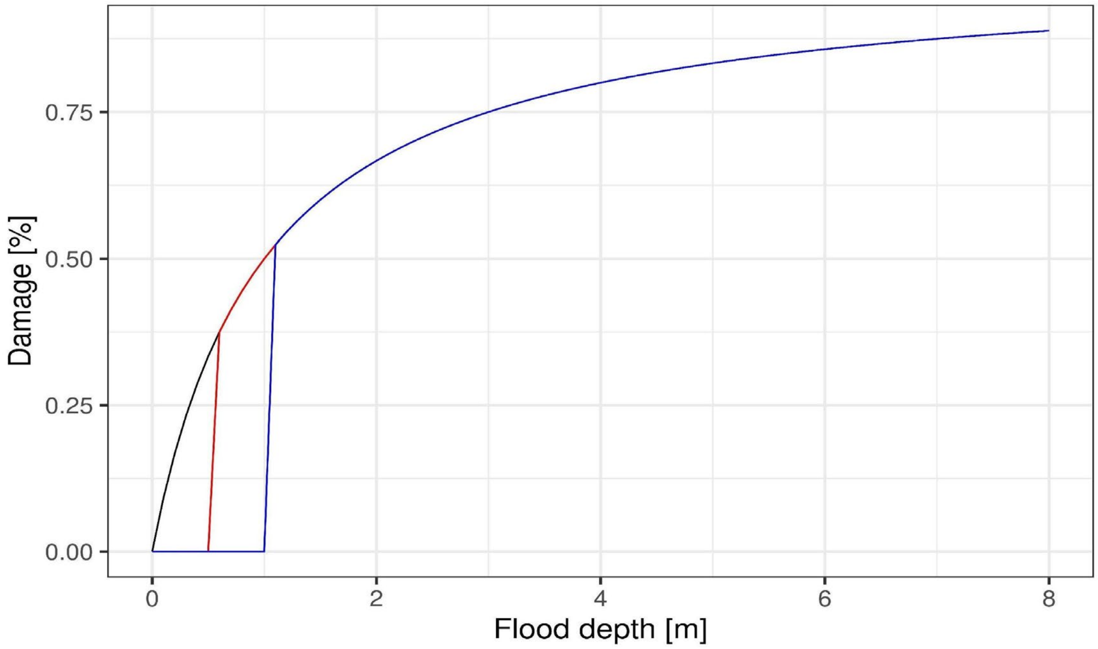

Figure 2.5.1: The depth-damage function used in DIVA and its modification for the model of flood proofing. The depth-damage function maps a flood depth to a damage as percentage of the asset value. The black curve is the original one - it has a half-damage depth of 1.0m, meaning that a flood depth of 1.0m causes 50% of the asset value as damage. The red and the blue curves are modified in order to model flood proofing of the capital stock of 0.5m (red) resp. 1.0m (blue). Flood depths below the flood proofing height do not cause any damage, flood depth above the flood proofing height causes the same damage as for unproofed assets.

To estimate the unit cost for flood proofing measure we refer to the few available case

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studies, collected by Aerts (2018) and shown in Table 2.5.1.

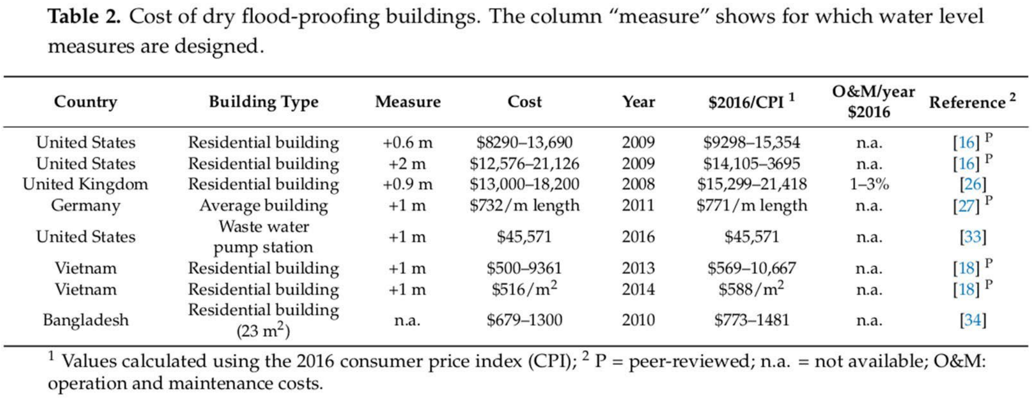

Table 2. Cost of dry flood-proofing buildings. The column "measure" shows for which water level measures are designed.

Country	Building Type	Measure	Cost	Year	\$2016/CPI [1]	O&M/year \$2016	Reference [2]
United States	Residential building	+0.6 m	\$8290–13,690	2009	\$9298–15,354	n.a.	[16] P
United States	Residential building	+2 m	\$12,576–21,126	2009	\$14,105–3695	n.a.	[16] P
United Kingdom	Residential building	+0.9 m	\$13,000–18,200	2008	\$15,299–21,418	1–3%	[26]
Germany	Average building	+1 m	\$732/m length	2011	\$771/m length	n.a.	[27] P
United States	Waste water pump station	+1 m	\$45,571	2016	\$45,571	n.a.	[33]
Vietnam	Residential building	+1 m	\$500–9361	2013	\$569–10,667	n.a.	[18] P
Vietnam	Residential building	+1 m	\$516/m^2	2014	\$588/m^2	n.a.	[18] P
Bangladesh	Residential building (23 m^2)	n.a.	\$679–1300	2010	\$773–1481	n.a.	[34]

[1] Values calculated using the 2016 consumer price index (CPI); [2] P = peer-reviewed; n.a. = not available; O&M: operation and maintenance costs.

Table 2.5.1: Available case studies for dry floodproofing. This table is directly taken from Aerts (2018).

The table shows data from different countries, for different flood proofing heights in different years. As there is rather little data, we compile this into one generic number that defines the unit cost of flood proofing. In order to do so, we exclude the German case study as the cost per length is not useful for us. The Bangladesh case study is excluded as the proofing height is unknown. The second Vietnam case is excluded as it seems to be a case of a wrongly assigned country. We also exclude the example of the Wastewater pump station as it is not compatible with our calculation, which is as follows:

- We scale every case study to the cost per person affected. For the US, the average number of occupants in U.S. households was 2.64 in 1990 and 2.52 in 2019 (University of Michigan, 2020). We interpolate linearly to get values for the years of the case study (both are from 2009 – the average number of occupants in U.S. households is thus estimated as 2.56). For the UK, we find a 2008 average household size of 2.36 people (Bentley and McCallum, 2019) . For Vietnam, available data suggest that average floor area per person was 22.8m² in 2017 and 16.7m² in 2009 (Vietnamnews, 2017), which interpolates to 20.5m² in 2014.Also for Vietnam, average household size was 3.6 persons in 2019 and 3.8 persons in 2009, interpolating to 3.72 persons in 2013.
- The average cost per person is then scaled to a flood proofing height of 1.0m
- This unit cost (per person per m height) can be averaged over all case studies to get an average unit cost of US$_{2016}$ 6,784 (see Table below).
- We finally relate these unit cost to the average infrastructure value per person, which is directly connected to the GDP per capita, scaled with factor 2.8 (Hallegatte et al. 2013). This leads to a relative unit cost of 0.12 times the local asset value per person.

Applying these calculations to the available case studies we calculate the average flood proofing cost as 0.12 times the value of the assets associated with one person (Table 2.5.2). Thus, we can compute the cost of flood proofing infrastructure in a segment as

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the population per segment is available. Further, the flood proofing costs are related to the values of existing infrastructure, allowing for subnational variations in these costs. Maintenance costs for flood proofing of buildings are assumed to be zero, as we assume that these costs are included in ordinary maintenance costs of buildings.

Casestudy	Year	Measure	Average Cost	Average Cost per person	Average cost per person/m	GDPC	Infra-structure per person	Factor average flood Infrastructure per person to proofing cost per person/m
US/residential building	2009	+0.6m	12,326	4,814	8,023	43,332	121,330	0.066
US/residential building	2009	+2m	18,900	7,383	3,692	43,332	121,330	0.03
UK/residential building	2008	+0.9m	18,359	7,779	8,643	43,504	121,811	0.07
VNM/residential building	2013	+1m	5,618	1,510	1,510	1,736	4,861	0.311
Average					**5,467**			**0.12**

Table 2.5.2: Computation of the flood proofing unit cost based on the available case studies.

Elevation of infrastructure

As elevation of infrastructure operates on the same stylized capital stock as flood proofing, it is also implemented by modification of the depth damage function. While the damage function of infrastructure that is neither flood proofed nor elevation starts at 0.0 meter flood depth and the depth damage function of flood proofed infrastructure is truncated up to the flood proof height, the depth damage function for elevated infrastructure is simply translated to the right on the x-axis (Figure 2.5.2).

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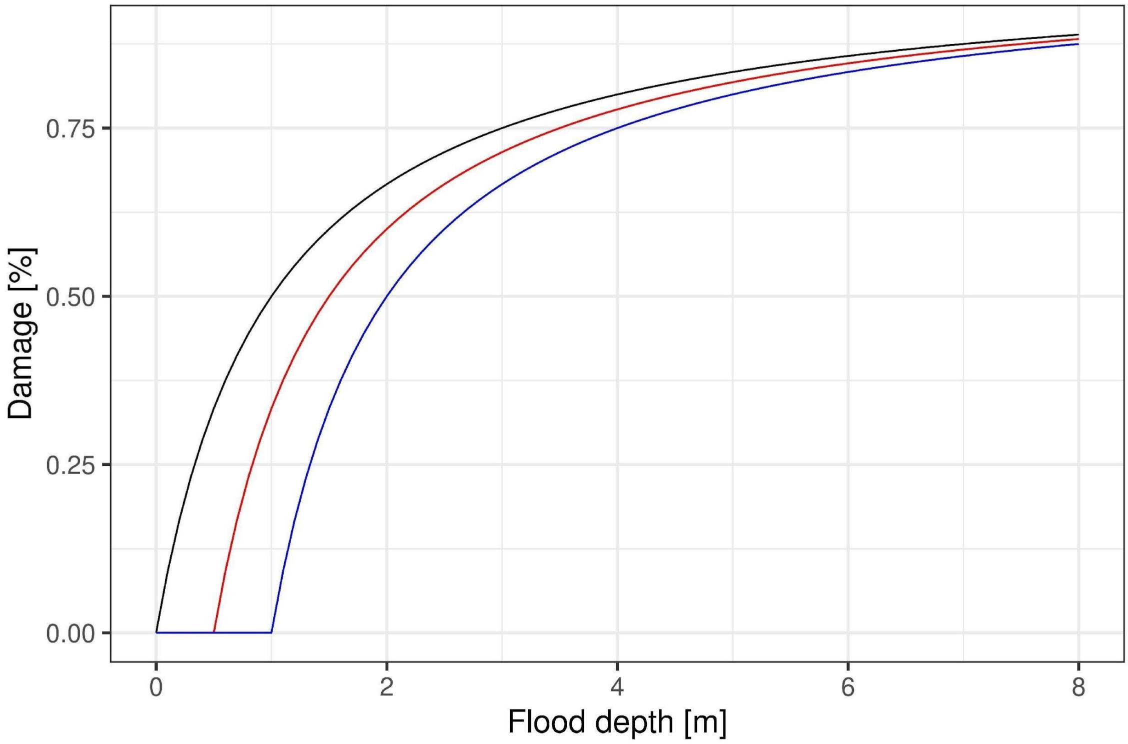

Figure 2.5.2: The depth-damage function used in DIVA and its modification for the model of infrastructure elevation. The black curve is the original one - it has a half-damage depth of 1.0m. The red and the blue curves are modified in order to model infrastructure elevation of the capital stock of 0.5m (red) resp. 1.0m (blue). Flood depths below the infrastructure elevation height do not cause any damage, flood depth above the infrastructure elevation height causes the same damage as for unelevated assets with a flood depth of actual flood depth minus the elevation height.

In the figure the black line shows the depth-damage function for non-elevated infrastructure, the red line for 0.5m elevated infrastructure and the blue line for 1.0m elevated infrastructure. The damage (as a fraction of the value of the infrastructure is simply shifted to the right: while unelevated infrastructure suffers 50% damage for 1.0m flood depth, 0.5m elevated infrastructure suffers 50% damage for 1.5m flood depth and so on).

The estimation of the unit cost of infrastructure elevation is done by the same method a s before. Aerts (2018) also provides a collection of infrastructure elevation costs based on available case studies (see Table 2.5.3).

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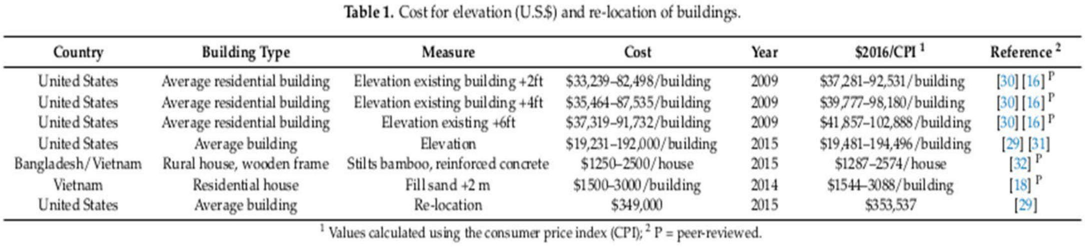

Table 1. Cost for elevation (U.S$) and re-location of buildings.

Country	Building Type	Measure	Cost	Year	$2016/CPI [1]	Reference [2]
United States	Average residential building	Elevation existing building +2ft	$33,239–82,498/building	2009	$37,281–92,531/building	[30] [16] ^{P}
United States	Average residential building	Elevation existing building +4ft	$35,464–87,535/building	2009	$39,777–98,180/building	[30] [16] ^{P}
United States	Average residential building	Elevation existing +6ft	$37,319–91,732/building	2009	$41,857–102,888/building	[30] [16] ^{P}
United States	Average building	Elevation	$19,231–192,000/building	2015	$19,481–194,496/building	[29] [31]
Bangladesh/Vietnam	Rural house, wooden frame	Stilts bamboo, reinforced concrete	$1250–2500/house	2015	$1287–2574/house	[32] ^{P}
Vietnam	Residential house	Fill sand +2 m	$1500–3000/building	2014	$1544–3088/building	[18] ^{P}
United States	Average building	Re-location	$349,000	2015	$353,537	[29]

[1] Values calculated using the consumer price index (CPI); [2] P = peer-reviewed.

Table 2.5.3: Available case studies for dry infrastructure elevation. This table is directly taken from Aerts (2018).

The same steps as before lead to infrastructure average elevation unit cost (per person per m height) of $\text{US\$}_{2016}$ 18,599 (see Table 2.5.4). We can also relate these unit costs to the average infrastructure value per person and get a relative unit cost of 0.19 times the local asset value per person.

Casestudy	**Year**	**Measure**	**Average Cost**	**Average Cost per person**	**Average cost per person /m**	**GDPC**	**Infrastructure per person**	**Factor average flood proofing cost per person/m to Infrastructure per person**
US/residential building	2009	+0.61 m	64,906	25,354	36,646	43,332	121,330	0.3
US/residential building	2009	+1.22 m	68,979	26,945	22,086	43,332	121,330	0.19
US/residential building	2009	+1.83 m	72,373	28,271	15,449	43,332	121,811	0.13
VNM/residential building	2014	+2m	2,316	623	213	1,736	4,861	0.12
Average					**18,599**			**0.19**

Table 2.5.4: Computation of the infrastructure unit cost based on the available case studies.

Experiments and results

The additional measures have been implemented in the DIVA model as described above. Then runs with the four additional adaptation options have been performed for the EU (EU-level, country-level and nuts2-level) using climate and socio-economic scenarios as in the COACCH scenario matrix (Hof et al., 2018). For Flood proofing and infrastructure elevation we assumed that all infrastructure in the 1-in-100-year floodplain will be subject to the measure. As sea-level rises, the 1-in-100-year floodplain increases and thus the amount of assets affected by the measure increases over time. Both, flood proofing and infrastructure elevation are performed to heights of 1.0m. Coastal retreat is modelled as a reactive retreat - all population and assets that fall below the 1-in-1 year water level are moved out of the coastal zone.

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The results of these simulations on EU28-level are shown in Figure 2.5.3. According to our assumption that the additional adaptation measures are secondary measures, the protection cost are the same under each additional adaptation measure. As the amount of protected coast varies only with the socio-economic development which is quite similar for the EU28 over the SSPs used, the percentage of protected coast is also quite similar overall scenarios, ranging from 79-86 percent. This value is rather high, reflecting that the EU is a wealthy region with a densely developed coastline that will be well protected at least over the 21st century. The additional adaptation measures thus apply only to 15-20 percent of the coastline.

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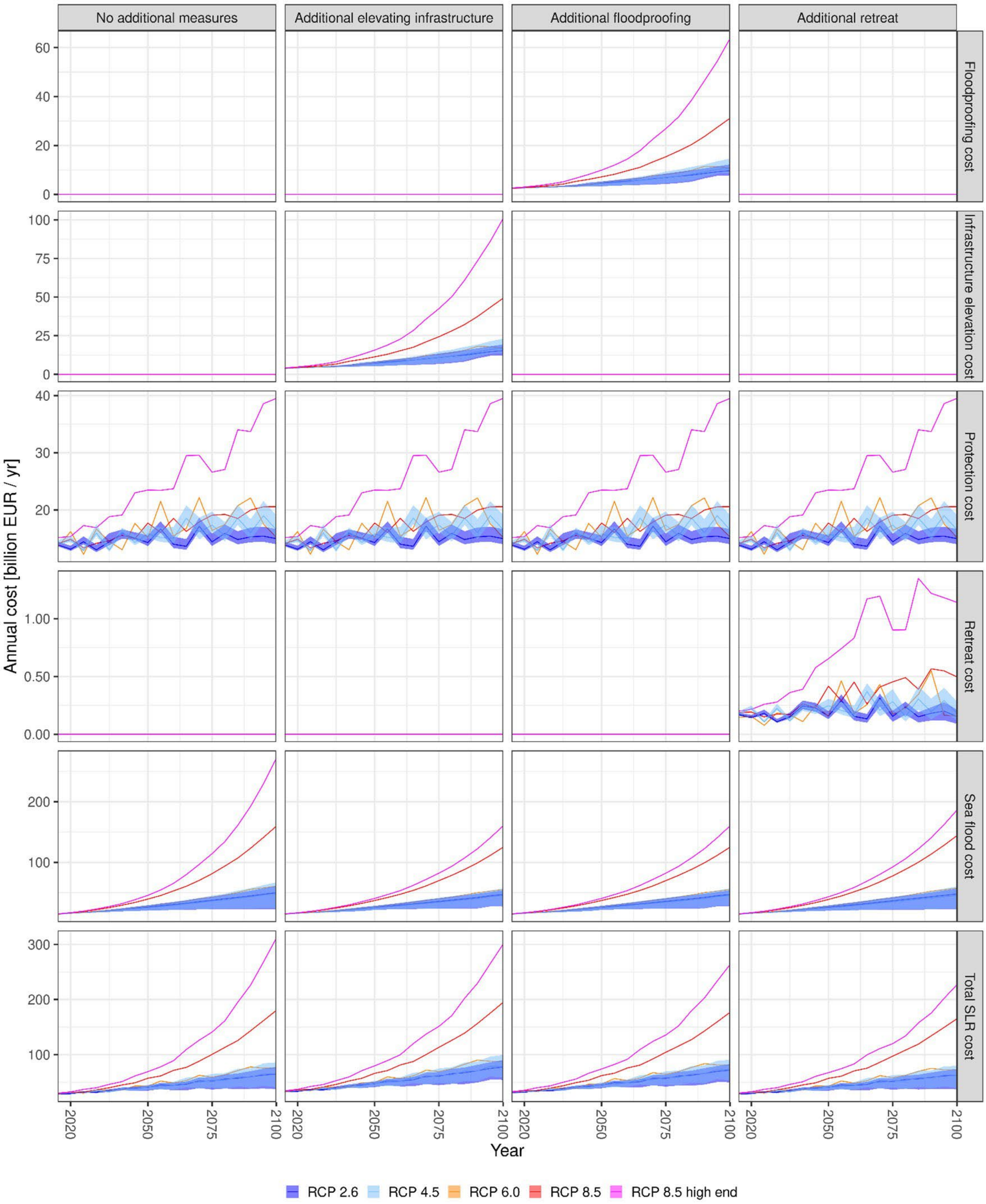

Figure 2.5.3: Results of the simulations with additional adaptation measures.

As Figure 2.5.3 shows, all additional measures reduce the total cost of SLR in comparison to the case with no additional measures. Each additional measure adds a specific cost component. In the configuration used for these experiments, the cost of coastal retreat is up to two orders of magnitude lower than the cost for floodproofing and infrastructure elevation, while the remaining damages reduced slightly more for infrastructure elevation and floodproofing. Comparing these two measures,

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infrastructure elevation has a higher cost than floodproofing, but the reduction of damages is similar for both measures. Comparing the total cost over time, we find that additional retreat causes the lowest total cost, while the highest total costs are associated with coastal protection without any additional measure. This result is not surprising: coastal retreat moves population and assets out of the coastal zone - affected infrastructure can not be subject to flooding anymore. With floodproofing and elevation of infrastructure the assets remain in the coastal zone and are still exposed to future flooding.

At country level, these observations hold also for most countries, with little exceptions (Fig. 2.5.4). For some countries, additional infrastructure elevation or flood proofing measures induce higher cumulative SLR cost than adaptation by coastal protection without any additional measures. This is for instance the case for Denmark and Sweden.

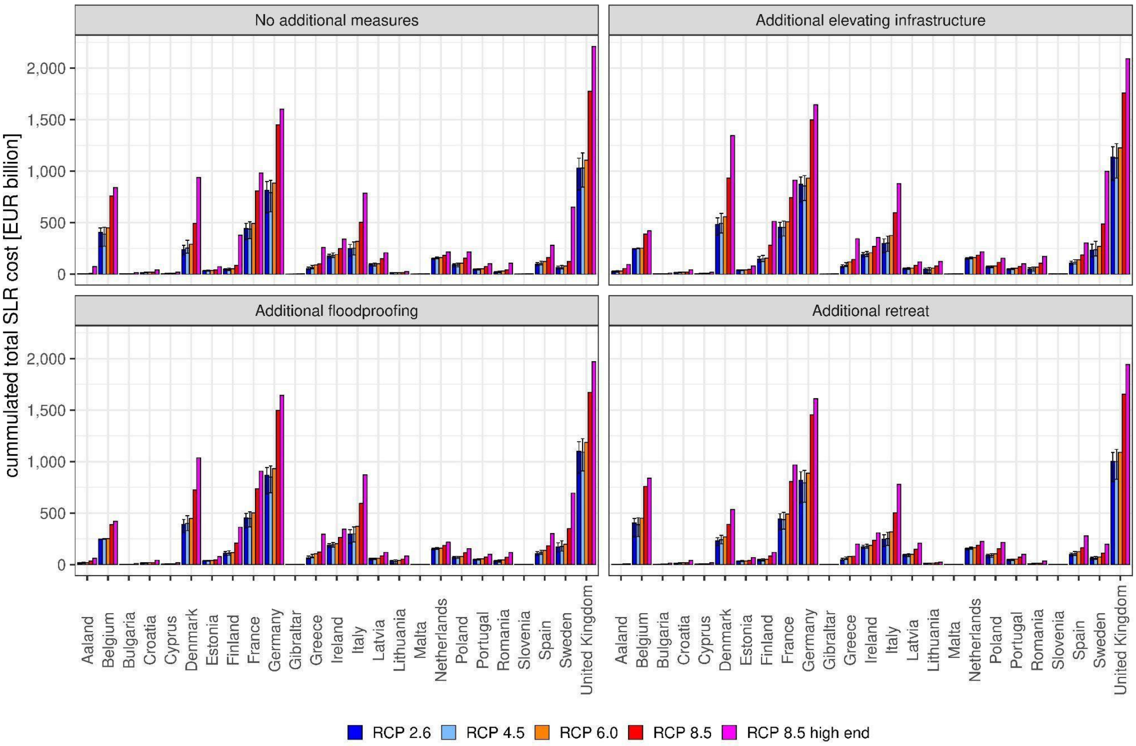

Figure 2.5.4: total cost of sea-level rise during the 21st century for all 22 coastal EU countries and the UK under the four scenarios of additional adaptation used in this study.

For other countries, for instance Belgium, the total cost under additional retreat is significantly higher than the total cost under additional flood proofing respectively infrastructure elevation. This might be caused by the elevation-slope structure of the infrastructure in these specific cases, and it shows that the effectiveness of such additional adaptation measures can not be assessed in a general way, but needs to be analysed on a case-to-case basis. Further research should explore the relationship between the involved parameters and data to better understand how the effectiveness of such additional adaptation measures can be analyzed.

2.5.2 River Flooding

Flood proofing of infrastructures

This section is a continuation of the river flood model explained in D2.3, with added adaptation assumptions. We use an integrated assessment model CLIMRISK-RIVER to project climate impacts of river flooding under different flood adaptation assumptions (Ignjacevic, 2020). According to the authors, the model's main purpose is the emulation of the more computationally complex hydrological model GLOFRIS. The GLOFRIS modelling cascade uses forcing data from EU-WATCH over the period of 1960-1999 as the baseline for forcing the hydrological model PCR-GLOBWB, used for the flood inundation modelling. GLOFRIS relies on the HYDE database as a baseline for generating baseline socioeconomic data. This data consists of gridded percentages of built-up area, population and GDP projections. For more information about the GLOFRIS model, please refer to the original paper (Winsemius et al. 2013).

River flood adaptation standards are already in place in many areas in Europe. A comprehensive global database - FLOPROS - of observed and modelled current river protection standards has recently been compiled (Scusollini, 2016). This data is available at the state level and is currently available for 2,683 states in the world in the form of river return periods against which the state is protected. The flood protection data used in this research consists of three future flood adaptation assumptions. The first two are directly derived from the FLOPROS database:

- *Baseline Height Standards (BaseHeightStd)*, which assume that the protection infrastructure is maintained at the baseline year *height* in the future and allow the river flood risk to vary over the course of the century. This scenario does not imply any additional river flood adaptation.
- *Baseline Probability Standards (BaseProbStd)*, which assume that the protection standards are updated so as to keep the baseline flood probability constant. This scenario does imply additional river flood adaptation as the flood protection standards are upgraded according to the varying natural factors in order to maintain constant flood probability. Regardless of the constant flood probability, the flood-related damage could still vary with the amount of exposed assets and the severity of flooding.

In addition to existing standards, the alternative scenario considers an optimal level of adaptation. Using cost-benefit analysis, policymakers' desired economic decision-making has been taken into account when designing the optimal level of river flood protection (Ward et al., 2017):

- *Optimal Standards (OptimalStd)*, which assume that all states behave in an economically optimal manner and invest today in the level of

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protection that would yield the highest net present value (NPV) over the twenty-first century.

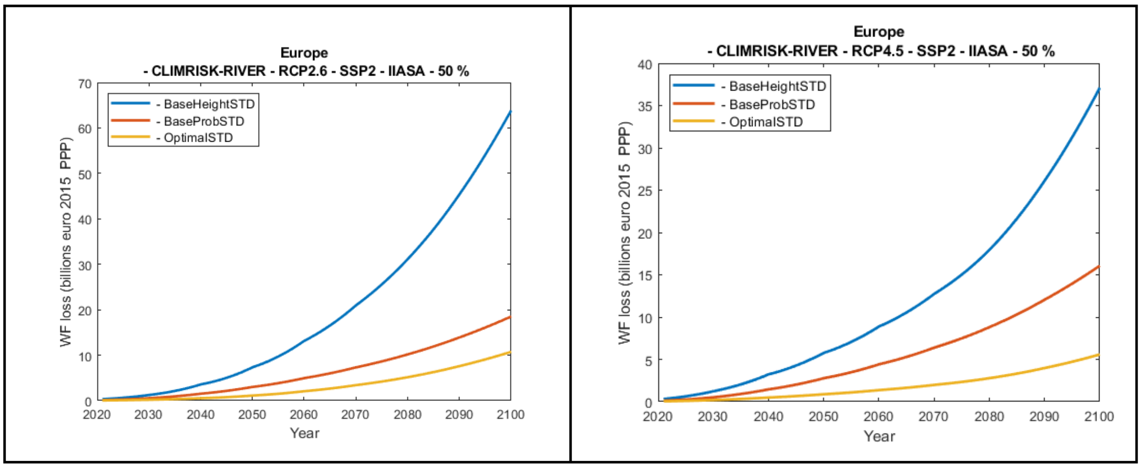
In addition to the above-mentioned flood adaptation assumptions, a final case - *No Standards (NoStd)* - is used for comparison. The *NoStd* scenario assumes that no cells are protected against any potential river floods, thereby ignoring existing protection standards as modelled in FLOPROS. Although not a realistic adaptation assumption, the *NoStd* scenario helps us understand how important flood protection standards are in estimating the flood damages in an IAM.

In cases where optimal protection data is missing for some cells due to, for example, missing future projections of socioeconomic data, we assume that the protection is maintained at the *BaseHeightStd* level.

Results

We begin the results presentation with the European-wide results. Figure 2.5.5 shows the impact of river flood adaptation assumptions on climate-related damage in an IAM. From the figure it is apparent that climate scenario plays a role in limiting the river flood adaptation, up to 2.5 times in 2100 under the RCP6.0 scenario compared to the RCP8.5 scenario.

Note that RCP2.6 shows slightly higher damage due to the fact that some cells, especially in Northern Europe, can experience benefits of climate change with increasing temperature, an effect that is limited under the RCP2.6 scenario.



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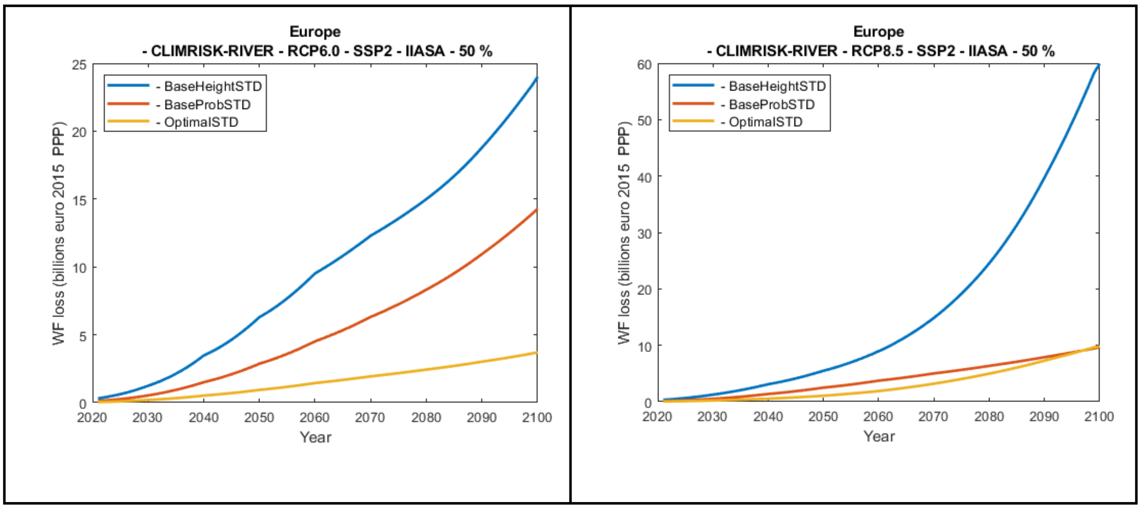
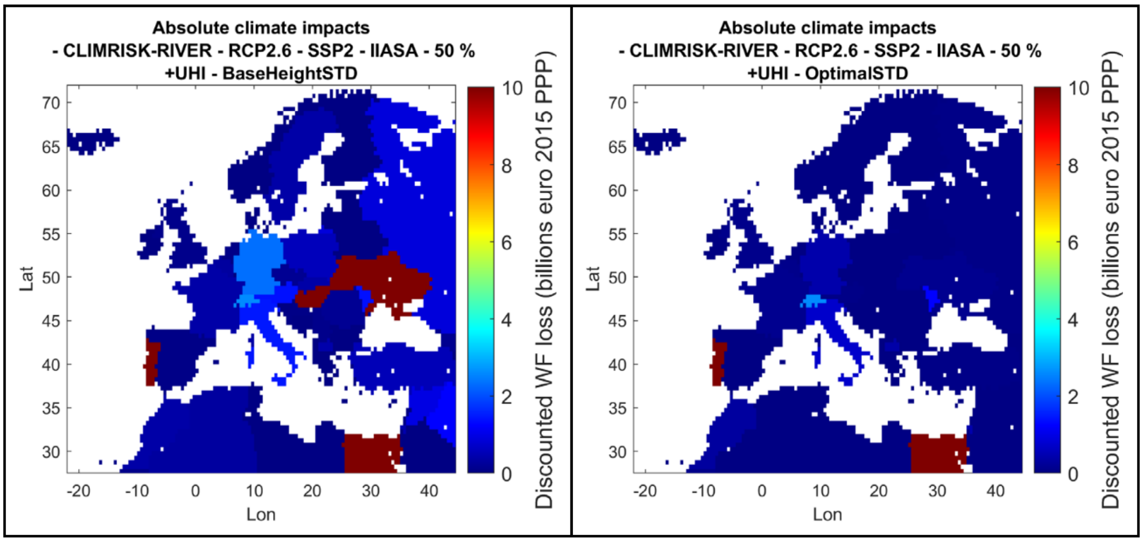


Figure 2.5.5: Adaptation matters: annual ΔEAD in CLIMRISK-RIVER under different protection standards and climate scenarios. Socioeconomic scenario: SSP2.

Country level

With CLIMRISK-RIVER, river flood impact estimates in Europe can be aggregated to a country-level. The damage estimates are presented in terms of discounted Δ*EAD* relative to the discounted GDP for the period 2010 - 2100. In figure 2.5.6, we present such estimates for RCP2.6, RCP4.5, RCP6.0 and RCP8.5 using the baseline and optimal flood protection standards. From the figure, it is clear that flood adaptation plays a more important role in flood risk mitigation than climate mitigation. Countries like Hungary, Moldova, Germany and Italy stand to gain the most from flood adaptation. Although Portugal is expected to have a relatively high river flood risk, the benefits of flood adaptation are relatively low since the current standards in place are already high.



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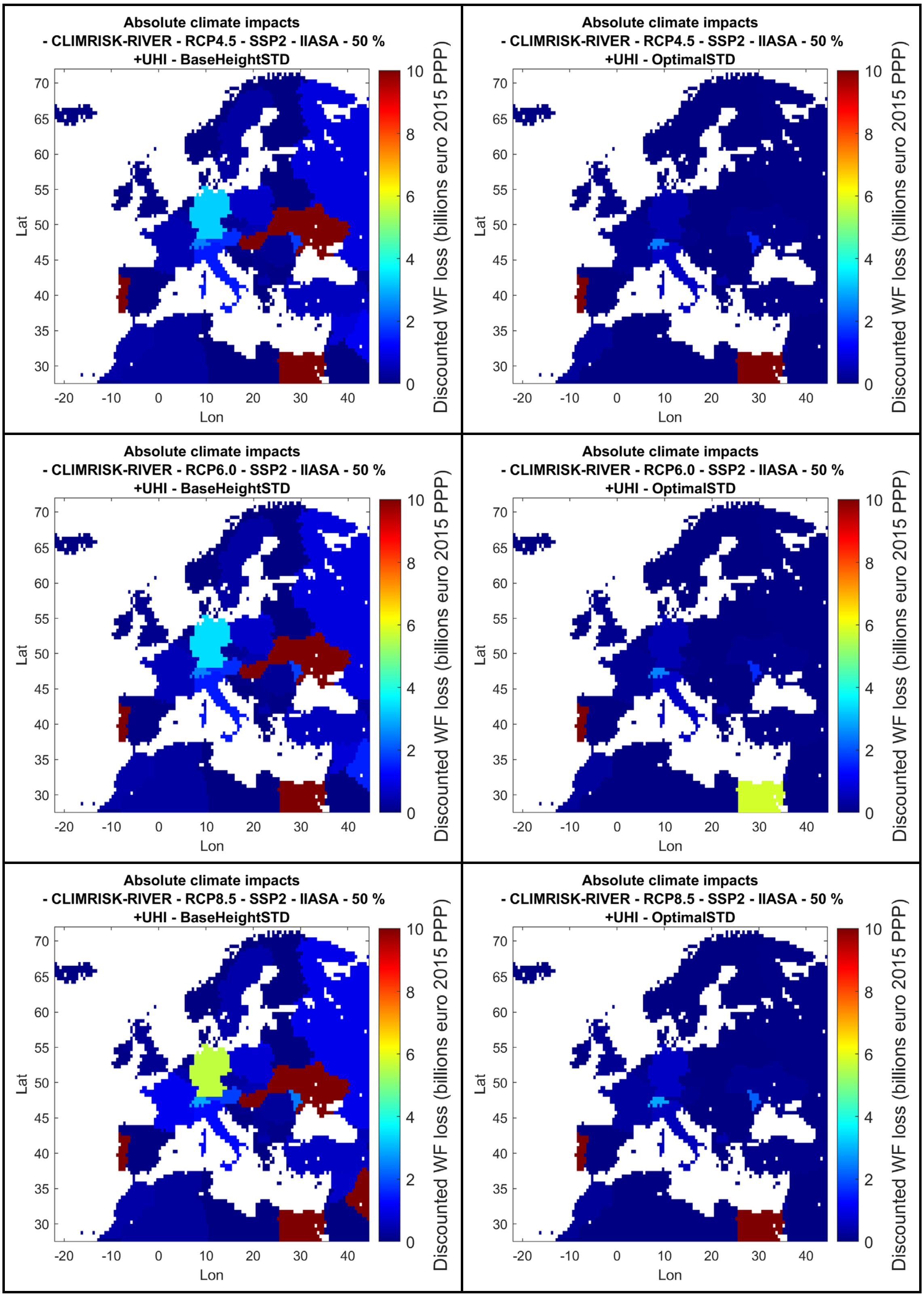

Absolute climate impacts
- CLIMRISK-RIVER - RCP4.5 - SSP2 - IIASA - 50 %
+UHI - BaseHeightSTD

Absolute climate impacts
- CLIMRISK-RIVER - RCP4.5 - SSP2 - IIASA - 50 %
+UHI - OptimalSTD

Absolute climate impacts
- CLIMRISK-RIVER - RCP6.0 - SSP2 - IIASA - 50 %
+UHI - BaseHeightSTD

Absolute climate impacts
- CLIMRISK-RIVER - RCP6.0 - SSP2 - IIASA - 50 %
+UHI - OptimalSTD

Absolute climate impacts
- CLIMRISK-RIVER - RCP8.5 - SSP2 - IIASA - 50 %
+UHI - BaseHeightSTD

Absolute climate impacts
- CLIMRISK-RIVER - RCP8.5 - SSP2 - IIASA - 50 %
+UHI - OptimalSTD

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Figure 2.5.6: Country-level annual ΔEAD in CLIMRISK-RIVER under current and optimal flood adaptation standards using different climate scenarios. Socioeconomic scenario: SSP2

In Europe, damages form a combined total of around €67 billion of discounted total Δ*EAD* in the top 10 countries under the RCP 2.6 and €75 under RCP 6.0 for the baseline protection standard assumption. This damage can be significantly reduced through applying the optimal flood protection policy, bringing the total damage down to around €27 billion under both RCP 2.6 and RCP 6.0. We can conclude that around €50 billion euros in discounted damages could be saved if optimal adaptation is in place in the 21st century. In some cases, it is possible for the damage under RCP 2.6 to be higher than under RCP 6.0 scenario due to varying natural factors accounted for in the GLOFRIS model. These factors include precipitation, temperature, evaporation and the underlying hydrological processes. In addition, certain regions could become dry or wet with increasing temperature or switch between wet and dry periods throughout the twenty-first century depending on similar factors. Such factors ultimately determine the total damage due to river flooding.

Europe ΔEAD	Climate Scenario RCP 2.6		Climate Scenario RCP 6.0	
Country	*BaseHeightStd*	*OptimalStd*	*BaseHeightStd*	*OptimalStd*
Hungary	35.30	0.01	40.90	0.02
Portugal	23.52	23.49	24.72	24.69
Switzerland	2.09	2.09	2.03	0.57
Germany	2.31	0.34	2.77	0.47
Italy	1.19	0.71	1.17	0.67
Austria	1.13	0.04	1.35	0.07
Poland	0.47	0.02	0.55	0.02
Turkey	0.42	0.08	0.48	0.07

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North Macedonia	0.40	0.38	0.40	0.38
Slovakia	0.30	0	0.45	0.36

Table 2.5.5: Top 10 most endangered countries in Europe in the 21st century, as measured by the discounted total ΔEAD (billions € 2015) due to climate change. The presented discounted damage estimates refer to the sum of 0.5° × 0.5° cells belonging to a specific country for SSP2 scenario using IIASA projections.

Local level

In addition to the country-level estimates of the benefits of river flood adaptation, local-scale results are also presented in this section. The process involves estimating the discounted value of river flood damage for two flood adaptation standards, *BaselineHeightStd* and *OptimalStd.* In addition to the local scale maps, we also define city-cells ie. derive which cells fall under the definition of all the cities in Europe and present the estimates for the top 10 cities that stand to gain most from implementing the optimal flood adaptation standards. Table 2.5.5 illustrates the effect that flood adaptation standards have on the expected flood damage due to climate change. Estimates are available for scenario combinations RCP2.6, RCP4.5, RCP6.0 and RCP8.5.

Local scale map data are also available for the specified scenarios for Europe. The results indicate that the area around the Rhine river basin would benefit from additional flood adaptation. There are also clear benefits to river flood adaptation in Eastern Europe, around the northern coast of the Black Sea (Ukraine).

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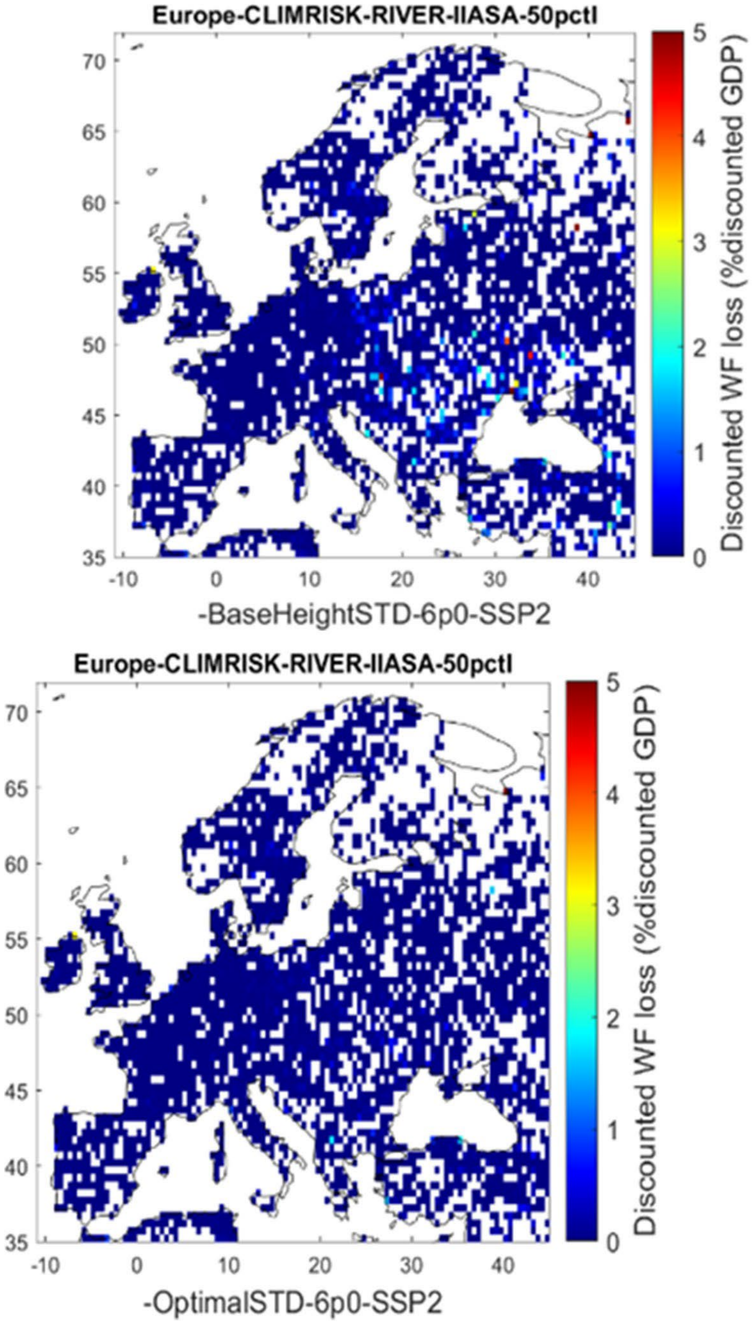

Figure 2.5.7: Discounted annual expected damage of CLIMRISK-RIVER on a grid cell level for BaseHeightSTD (top panel) and OptimalSTD (bottom panel) flood protection standard assumptions in Europe. Scenario: RCP6.0 - SSP2.

The local-scale advantage of the CLIMRISK-RIVER model can be fully utilized on city-cell level data. In the following subsection, we focus on cells most severely affected by future flood risk and identify cities that fall within their boundaries.
The most affected city is expected to be Gyor, HU with around €35-40 billion in discounted river-flood damages, most of which can be mitigated if the adaptation standards in place were optimal. Cities like Porto, Zurich and Perth all have optimal

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adaptation standards already in place. In relative terms, optimal adaptation leads to near complete mitigation of all river-flood related risk for many cities in Europe.

Europe	Country	Climate Scenario RCP 2.6		Climate Scenario RCP 6.0	
City-cell		*BaseHeightStd*	*OptimalStd*	*BaseHeightStd*	*OptimalStd*
Gyor	HU	34.42	0	39.98	0
Porto	PT	23.41	23.40	24.62	24.61
Zurich	CH	2.09	2.09	2.03	2.03
Perth	GBR	1.15	1.13	1.15	1.15
Frankfurt	DE	0.68	0.02	1.06	0.03
Vienna	AU	0.85	0.04	1.04	0.07
Cologne	DE	0.43	0.03	0.72	0.04
Szeged	HU	0.66	0	0.67	0
Florence	IT	0.49	0.45	0.44	0.41
Hamburg	DE	0.23	0.05	0.30	0.06

Table 2.5.5: Top 10 most endangered cities in Europe in the 21st century, as measured by the discounted total ΔEAD (billions € 2015) due to climate change. The presented discounted damage estimates refer to the sum of 0.5° × 0.5° cells belonging to a specific city for SSP2 scenario using IIASA projections.

The limitation of the current method involves the lack of city-specific data which is approximated from cell-level data available in the CLIMRISK model. Nevertheless, the results of the current model present a first look at the consequences of climate change and the benefits of flood adaptation in the context of river flooding.

2.5.3 Policy effectiveness of urban coastal adaptation strategies to avoid socio-economic tipping points in cities under high-end sea level rise

This project has received funding from the European Union's Horizon 2020 research and innovation programme under the Grant Agreement No ***776479.***

This section addresses the effectiveness of urban coastal adaptation strategies with the help of a stylized case study simulating long-term adaptive behaviour in a city. The objective is to assess the effectiveness of four different flood risk policies to avoid the tipping point of a sudden house price collapse. For this purpose, we simulate many possible futures for a city, and examine how flood risk and the house price develop in these futures under different policies.

This assessment of policy effectiveness for avoiding socio-economic tipping points builds on the operationalisation of the socio-economic tipping point concept in COACCH Deliverable 3.1, as elaborated in Van Ginkel et al., 2020. The used analytical instrument, namely a stepwise approach to identification and impact analysis of socio-economic tipping points has been developed and introduced in COACCH Deliverable 3.4 (section 2.5) and Van Ginkel et al., 2021 (Under Review). We explicitly assess how effective policy is when the climate tipping point of strongly accelerating sea level rise - due to Marine Ice Sheet Instability (MISI) or Marine Ice Cliff Instability (MICI) - would occur. The likelihood of this climate tipping point (CT1) has been addressed in COACCH Deliverable 3.2, section 2.1

Recap of analytical instrument: model set-up and reflected uncertainties

This section recapitulates the set-up of the model, which was initially developed in Deliverable 3.1, and is summarized with updated parameters here (see Van Ginkel et al., 2021, under review).

In each model run, a possible future for the archetypical city – which has characteristics of Rotterdam - (Figure 2.5.8) is simulated. The city consists of an unembanked 'outer-dike' area A, and an embanked 'inner-dike' area B, which is protected by a man-made levee. Each year, the most extreme water level is evaluated, by adding stochastic storm surges to the mean water level in the sea level rise scenario. The model evaluates possible near misses and flood events and evaluates the flood risk (annual expected damage). It also simulates the risk perception of the residents in both areas, which is determined by their recent experiences with floods. Then, it calculates the house price in two ways, after Botzen et al. (2009) and Haer et al. (2017). It either assumes full rational behaviour, at which the rational flood risk is discounted for in the house price. Or it assumes boundedly rational behaviour, at which the perceived (rather than the rational) flood risk is discounted for in the house price. In the boundedly rational housing market, the flood risk is overestimated if the risk perception is high (for example just after a near miss event), meaning that the house price is lower than can be rationally expected. Vice versa, the flood risk is underestimated when the risk perception is low (for example when nothing happened many years in a row), meaning that the house price is higher than can be rationally expected.

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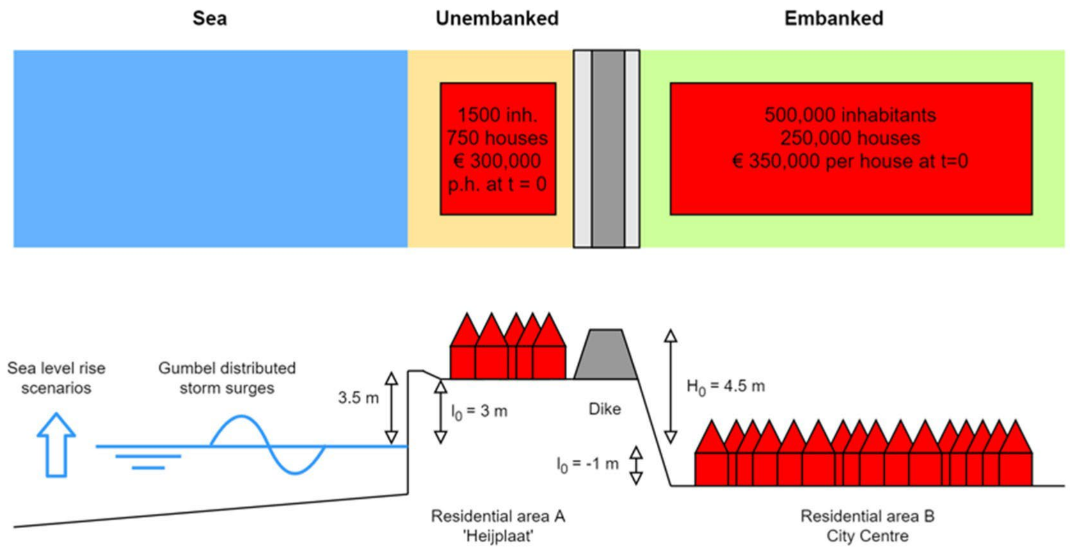

Figure 2.5.8: Schematic overview of archetypical coastal city with an unembanked and an embanked area.

In each experiment, the model is run for one unique setting of uncertainties (X), policy levers (L) and model relations (R), as shown in Figure 2.4.9. The sea level rise scenarios cover the IPCC likely range scenarios for RCP2.6, 4.5 and 8.5, as well as more extreme high-end sea level rise scenarios resulting from the climate tipping point of strongly accelerating sea level rise. The storm surge heights are stochastically drawn from an extreme value distribution for Rotterdam. The implementation times reflect the time it takes a measure to become effective, after the decision for its construction has been taken.

The outcome of each experiment is measured by two metrics (M): the house price in area A (M_a) and area B (M_b), from the year 2020 to 2200. Each experiment is evaluated on the occurrence of socio-economic tipping points, by time series analysis. In this tipping point evaluation, each house price time series is searched for points with abrupt changes of house price, indicating a transition from one to another (fundamentally different) stable state (Box 1).

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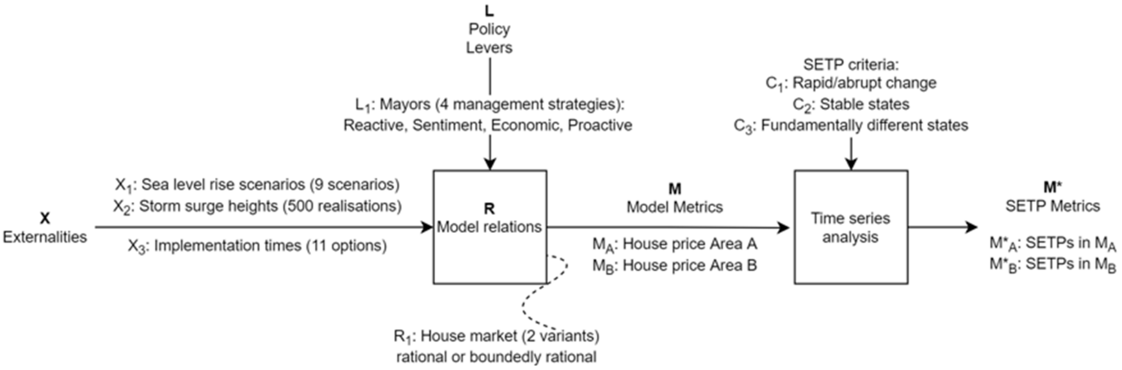

Figure 2.5.9: Schematic overview of each model run, using the XLRM-framework (Kwakkel, 2017)

In total 396,000 experiments were run, each with a unique combination of parameters X_1-X_3, R_1, and L_1. Per experiment, we explore whether the house tipping point does or does not (yes or no) occur in residential area A, and in residential area B.

Box 1: Defining the socio-economic tipping point

The climate change induced socio-economic tipping point (SETP) is defined by COACCH as a point of:

C1: rapid, abrupt change,

C2: separating a stable state before and after that point,

C3: and these states being fundamentally different.

This was operationalized for the housing price in this case as follows:

C1: a house price drop of more than 15% in one year,

C2: variance in the mean house price below some threshold,

C3: the mean house price before is 10% different from the house price after.

In this case study, we considered as policy relevant not only the perfect example of a tipping point in which all three criteria are met, but also the special situation where the house price remained unstable after the tipping point. Here, the house price is initially stable, then suddenly drops to a substantially different situation of instability. In the new situation, the house price keeps fluctuating (booms and busts) rather than converging to a new equilibrium. To be precise, this is the case where C1 and C3 are met, but C2 is only met for the state before, and not for the state after the 'tipping point'.

Description of assessed policies

The policies (L_1 in Figure 2.5.9) reflect four public sector flood risk management strategies. All four policies are examples of so-called ‘hard protection’ strategies (IPCC, 2019), meaning that they involve the heightening of man-made embankments to reduce the probability of floods. Note that in our case, there only is one embankment, which protects Area B. Hence, Area A does not benefit from any of the policies; it serves as a reference case for a ‘no adaptation’ strategy in an area currently protected by its natural elevation above current mean sea level.

The four policies reflect a continuum from reactive to proactive flood risk strategies. In the ‘reactive’ policy, adaptation is triggered by recent (near-) flood experiences. A near-miss event triggers a minor dike heightening of 0.5 m, an actual flood triggers a major dike heightening of 1 m. This strategy is sensitive to the ‘arbitrary’ order in which the stochastic storm surge events hit the city.

The ‘sentiment’ policy is slightly more proactive; in this policy, adaptation is triggered by threshold values in the *perceived* flood risk. Since flood risk perceptions depend on both the objective risk as well recent flood experiences, this strategy is sensitive to the arbitrary order in which the stochastic storm surge events hit the city.

The ‘economic’ policy is even more proactive, in this policy adaptation is triggered by threshold values in the objective flood risk. This is comparable to decision making based on a cost-benefit analysis. Because the random order in which stochastic storm surge events hit the city have no impact on the rational, objective flood risk, the economic policy is not affected by the arbitrary order in which the stochastic storm surges hit the city.

In the ‘proactive’ policy, adaptation is triggered by threshold values in the dike failure probabilities, as used to be the case in The Netherlands. A minor dike heightening (50 cm) is implemented if the return period of the flood protection falls below 10,000 year. A major dike heightening (1 m) is implemented if the return period of the flood protection falls below 2,000 year.

In all policies, the decision for a small dike heightening, with a default implementation time of 7 year, can be overruled by a decision for a large dike heightening, with a default implementation time of 12 year. In this case, the implementation time of the large dike heightening is shortened, depending on the time expired while doing the small dike heightening. This situation occurs when the decision to implement a minor dike heightening has already been taken, but this measure is not yet effective because it is still being implemented, and during this implementation time the threshold for a large measure is exceeded.

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Effectiveness of policies in avoiding tipping points

Figure 2.4.10 shows how effective the policies are in avoiding the socio-economic tipping point of an abrupt house price collapse. It also shows the impact of the uncertainty in storm surge heights, flood protection measure implementation time andschematisation of the housing market.

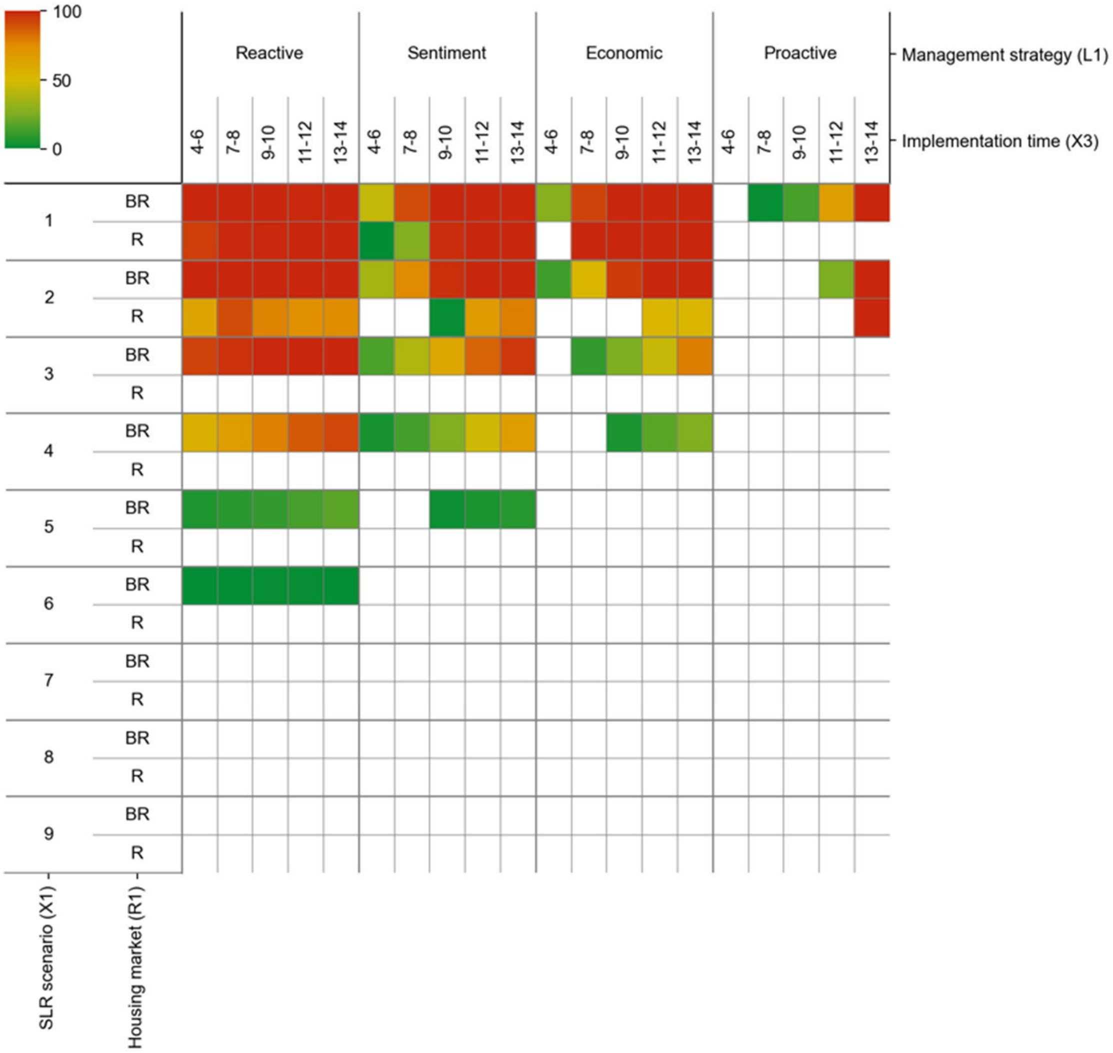

Figure 2.5.10*:* Effectiveness of flood protection policies in many possible futures, expressed in the probability (0-100%) of the sudden house price collapse (socio-economic tipping point) happening under this policy. In empty (white) grid cells, no house price collapses occur. Note that 'no tipping point' does not necessarily mean 'no need for action', see box 2. Note that the shown implementation time corresponds to a small measure (0.5 m dike heightening). The implementation time of a large measure (1 m) is a factor 12/7 ≈ 1.7 larger.

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The policy implications of the house price collapse tipping points are as follows. Clearly, the more proactive, the more effective a flood risk policy is in avoiding tipping points: the SETP likelihood strongly reduces from left to right in Figure 2.5.10.

Box 2: Warning: 'no tipping point' does not always mean 'no problem'

Note that in this context, tipping points are defined as the specific phenomenon of an abrupt, non-linear house price change towards a fundamentally different - stable or flickering - state (see box 1). This implies that some experiments may not have tipping points, but nevertheless have major policy implications.

For example, the house price may gradually fall to zero over the course of several decades without showing a tipping point like abrupt change (>15%) in any individual year. This happens to the unembanked Area A in many of the high-end sea level rise scenarios, especially with a fully rational housing market where the house price is less volatile because fluctuations in risk perception do not impact the house price. In these situations, Area A will eventually flood so frequently (or even permanently) that the expected damage to houses (discounted over the depreciation rate of the houses) equals their original value, meaning that the actual value of the house, and thus the house price, is 0.

When the climate tipping point of accelerating sea level rise happens (SLR scenario 1 and 2, Figure 2.4.10), there is a high likelihood that the socio-economic tipping point will happen as well. It is therefore crucial to monitor the early warning signals of accelerated melting dynamics of the ice sheets (Haasnoot et al., 2018).

If this climate tipping point happens, house price collapses can only be avoided with very proactive flood risk policies. Even in a proactive flood risk policy, the policy may fail when the implementation time of the measures becomes too long. In this context, note that the implementation time of large movable storm surge barriers is notoriously long. For example, the initiative to construct the Maeslant storm surge barrier protecting the city of Rotterdam was triggered by a flood in 1953. The formal decision for construction was taken in 1987, ten years later - in 1997 - the barrier became operational. Similarly, Venice was struck by a large flood in 1966 which triggered the discussion on constructinga storm surge barrier, the project was first tendered in 1975, started in 1987 and was finished in 2021[1]. In high-end SLR scenarios, such implementation times are too long to keep up with SLR. This means that the decision for construction of complicated floodprotection structures needs to be taken well before they need to be operational. Otherwise, the rate of SLR will exceed the capacity to respond.

In the IPCC SROCC (IPCC, 2019) likely range scenarios (SLR scenario 3-6), there still is a possibility that house price collapses happen, but only when assuming a boundedly rational housing market (see the rows labelled 'BR', Figure 2.4.10). Note that a main cause of these house price shocks is the strongly elevated risk perception of the city residents following a near miss or flood event. The policy implication of this is that house

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price fluctuations may be partly avoided by well informing and convincing residents (and other real estate owners) about the rational flood risk, so that the behaviour of the housing market is more towards the rational housing market in which no tipping points occur (see the rows labelled 'R', Figure 2.4.10).

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[1] These dates were retrieved from an ensemble of newspaper articles, academic papers and reports, as summarized on the Wikipedia pages:
https://en.wikipedia.org/wiki/MOSE and
https://en.wikipedia.org/wiki/Maeslantkering, latest accessed on June 7, 2021.

Policy insights for adapting road transport infrastructure to river floods (Deltares)

With respect to road transport and river floods, COACCH has focussed on two aspects. The first aspect is an improved assessment of direct infrastructural damage, i.e. what it would cost a road operator to hire a contractor to repair the road in the aftermath of a river flood. Deliverable 2.3 introduced a new refined approach to modelling these, and the results have been published in Van Ginkel et al., 2021 with an extended spatial domain (including EU candidate countries). The first part of this section recapitulates these results for the baseline climate, and for different climate scenarios with and without adaptation policy. Without adaptation, there is a strong increase in costs. However, with successful adaptation of river embankments to the new climate conditions, the increase of damage due to climate change can be reduced to an insignificant amount (order a few percent).

The second aspect addresses the vulnerability of the European road network to large systemic failure, or socio-economic tipping points, from different societal perspectives and at different spatial scales. In line with the findings of the direct damage assessment, we found that Europe is unlikely to experience a severe tipping-point like macroeconomic shock due to river-flood related road network disruptions, see Deliverable 3.4.

From these two results, one may conclude that there is no urgent need to 'climate-proof' the European road network specifically against river floods, except from keeping the protection levels of river embankments at the same protection level. This however, does not mean that there is no room for improving the road network. Even the most robust national networks appear to have weak spots, which may be flood-proofed to enhance the network robustness. The section will focus on guiding such robustness-enhancing policy. One key insight is that policy makers need an approach that is suitable for hotspot identification. COACCH has provided such an approach to identify the flood

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hotspots (part 1) as well as the most critical sections of a road network for overall network functionality (part 2).

Part 1: improved estimates of direct damage with object-based model
Figure 2.5.11 shows the direct damage to road infrastructure in the baseline scenario, for the old grid-based and the new object-based approach. The new approach (panel c) estimates the total costs at 230 million euro per year (2015 pricelevel). The interquartile range (50% confidence, panel d) ranges from 172-284 million euro. This is well below previous estimates with grid-based approaches with CORINE and LUISA land cover classifications (panel a).

Spatially, the risk is concentrated in Alpine regions and Scandinavian countries (Figure 2.5.12, panel a). When looking into the damage as a percentage of regional GDP, eastern European also pops up as a high-risk region (Figure 2.4.12, panel b). Recent research suggests that the high damage in Scandinavian countries could originate from a model artefact in the flood hazard modelling, which propagates to the damage modelling and leads to an overestimation of damage (Dottori et al, 2021, under review).

An important improvement of our new approach is that the results can be presented on the level of individual road segments. Figure 2.5.13 highlights three notable regions. In The Netherlands (Figure 2.5.13, panel a), the aggregated flood risk is low, but the fact that many important highways may be disrupted at the same time is nevertheless a reason for concern. Like in Figure 2.5.12, the Alps also pop up as a flood hotspot in Figure 2.5.13 (panel b). One concern is that many roads are located close to rivers, since both roads and rivers often follow the lowest and flattest part of the valley. This makes mayor roads in Alpine regions relatively flood-prone. Another flood hotspot is the E70 highway along the Sava River, from Zagreb – Croatia - to Belgrade – Serbia (panel c). For a high-resolution version and a further interpretation of this figure, see Van Ginkel et al., 2021.

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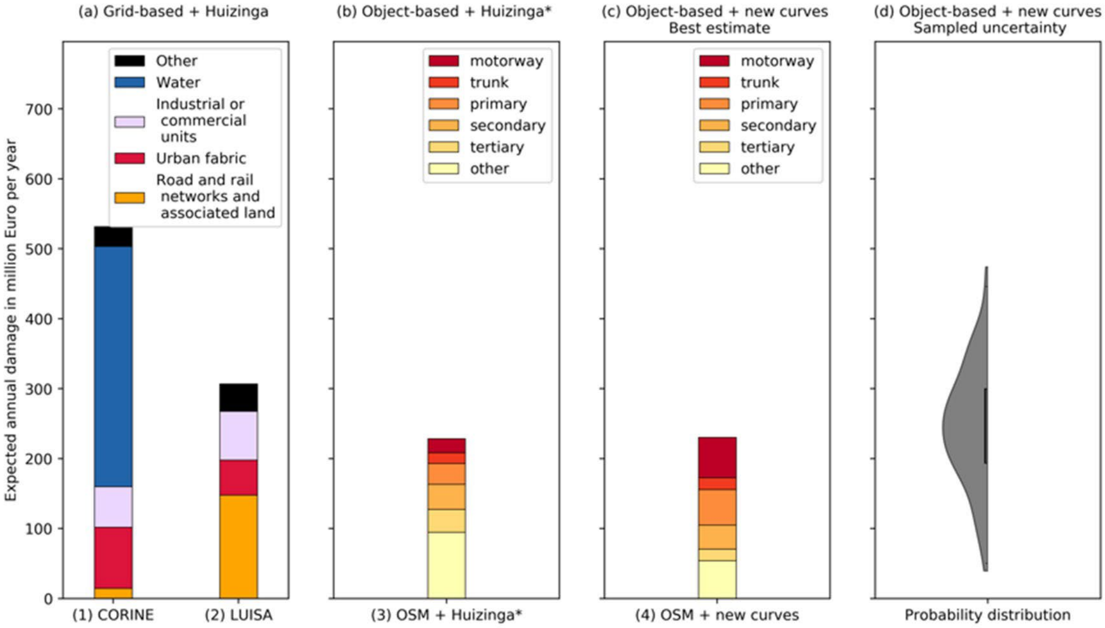

Figure 2.5.11: Flood risk of the European road network according to the traditional grid-based (panel a) and new object-based (panel c), including uncertainty analysis (panel d). This figure has been published in NHESS (Van Ginkel et al., 2021) and is licensed under a CC BY 4.0 open access license.

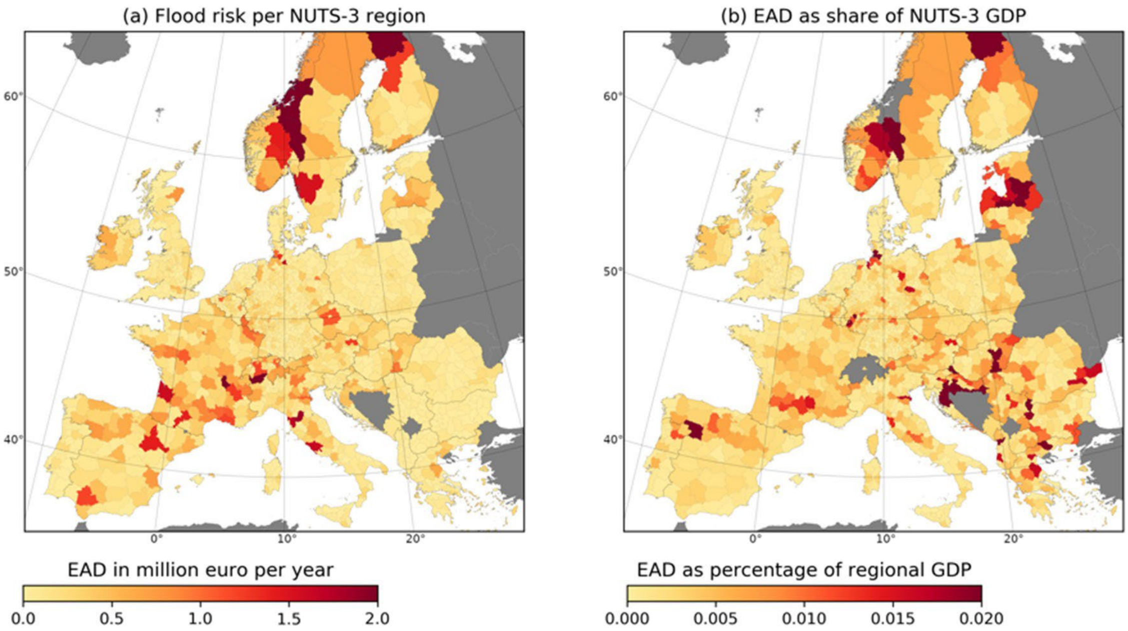

Figure 2.5.12: Distribution of road infrastructure river flood risk over Europe, spatially aggregated by NUTS-3 regions, in absolute terms (panel a, 2015-pricelevel) and as percentage of regional GDP. This figure has been published in NHESS (Van Ginkel et al., 2021) and is licensed under a CC BY 4.0 open access license.

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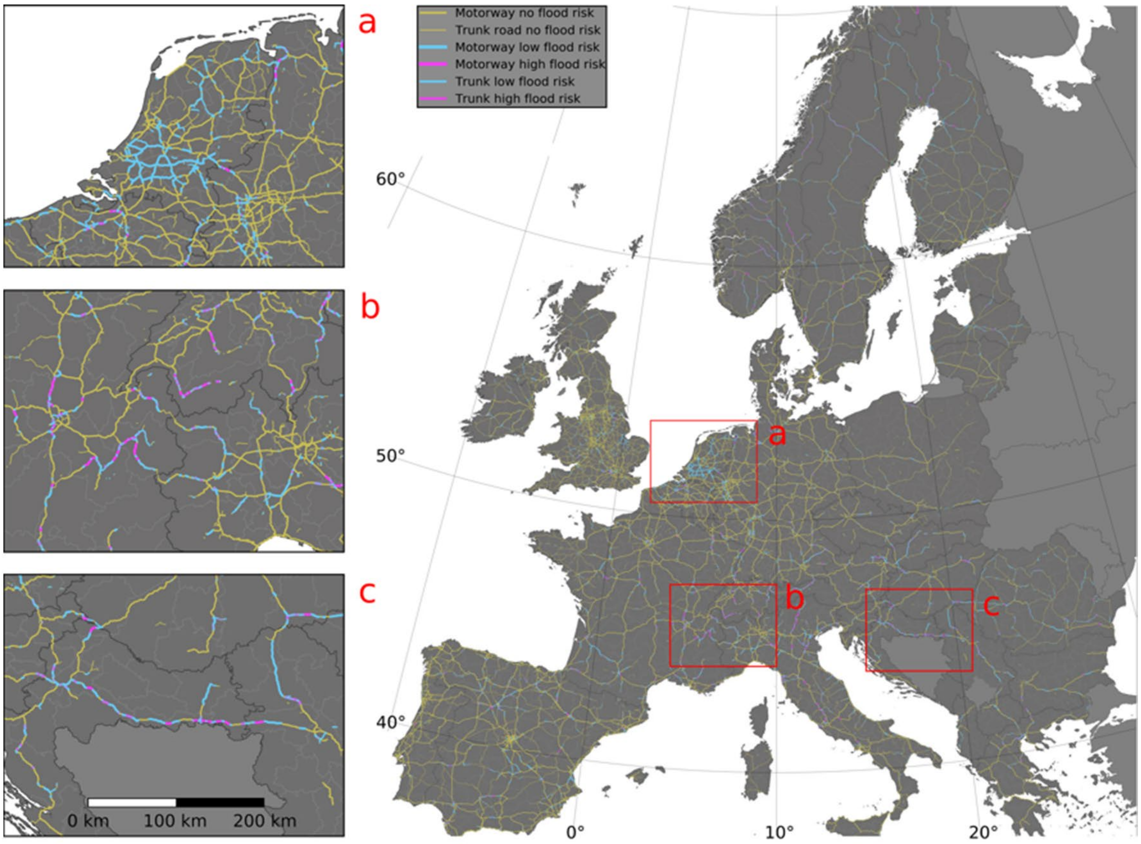

Figure 2.5.13: Flood risk of the European highway network. This figure has been published in NHESS (Van Ginkel et al., 2021) and is licensed under a CC BY 4.0 open access license. Road geometries © OpenStreetMap contributors 2019. Distributed under a Creative Commons BY-SA License.

How does the flood risk develop under climate change? First of all, it should be mentioned that continental-scale streamflow projections - from which the results are derived - are debated among flood modellers (e.g. Kundzewicz et al., 2016), because thus far there is no consistent climate-change trend in observed flood discharges in Europe (Hall et al., 2014, as cited in Dottori et al., 2021, preprint). Nevertheless, there is growing consensus that climate change will intensify floods in most parts of Europe. This trend is clearly observable in the ensemble run of river flood damage to road infrastructure in Figure 2.5.14.

Figure 2.5.14 shows that without adaptation, there most likely is a strong increase of road damage from river floods. These findings are consistent with the findings of PESETA-IV, see box 3. The PESETA-IV results are based on the same Eurocordex ensemble but take a slightly different approach to the damage modelling. Figure 2.5.14 also shows that if river embankments are continuously adapted to the new streamflow conditions, the increase in flood damage will be very small. The policy implication of this is that it is important to continuously monitor the trend in river discharge conditions,

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and to timely adapt embankments of river basins where an increasing trend in extreme river discharges can be observed.

Box 3: Comparison of COACCH and PESETA-IV results

In the context of PESETA-IV, Mulholland et al. (2021, under review) also study the impact of river floods on road transport infrastructure. This study builds on the COACCH literature review of road construction costs as published in Van Ginkel et al., 2021. Here we compare the results of both studies.

Concerning damage to roads, Mulholland et al. find a baseline EAD of € 315 million. This is above the COACCH baseline of € 230 million, but well within the corresponding 90% confidence interval from € 80-373 million, see Figure 2.4.11, panel d. The difference can likely be attributed to the different damage functions. COACCH developed new damage functions, which assumed that European motorways and trunk roads are slightly elevated above the ground level, resulting in lower damage for small inundation depths. Moreover, COACCH assumed a slightly lower maximum damage per road asset.

Besides road damage, Mulholland et al. also report damage to other types of transport infrastructure, namely seaports, airports and rail infrastructure. In total, they find a baseline EAD of € 1.6 billion of river flood damage to transport infrastructure, which is about one fifth of total river flood damage to all land use categories (including buildings and agriculture). Total transport infrastructure damage may increase from € 1.6 billion to € 2.6 billion under a 1.5°C, to € 2.6 billion under a 2°C, and to € 5 billion under a 3°C global warming.

Remarkably, Mulholland et al. find that rail contributes by far the largest share (1.1 of the 1.6 billion, i.e. nearly 70%) of total transport infrastructure damage. This contribution of rail nearly doubles the estimate of € 518 million by Bubeck et al. (2019). In Van Ginkel et al. (2021), we argued that the € 518 million could already be on the high side, because an econometric study by Doll et al. (2014) suggests that total rail damage is usually smaller than road damage. In contrast, the findings of Mulholland et al. suggest that rail damage is outnumbering the road damage. This discrepancy needs to be further investigated. If rail indeed would be such extremely more vulnerable than road infrastructure, this would have important policy implications.

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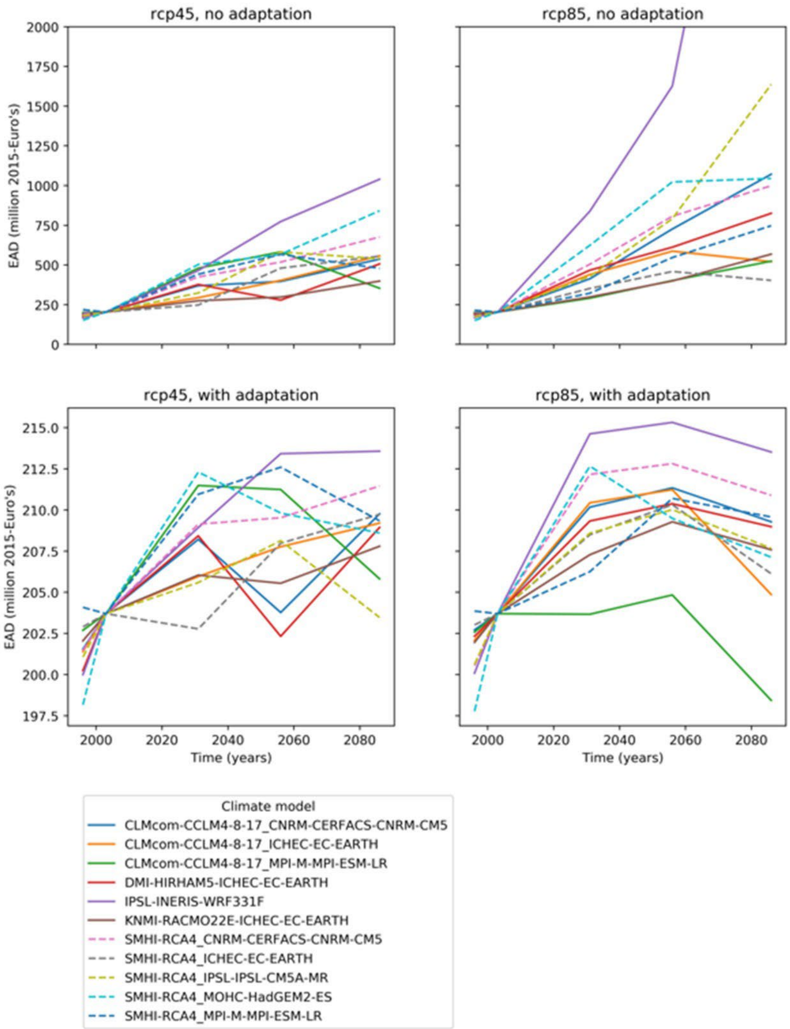

Figure 2.5.14: Change of actual expected damage under climate change scenarios, under RCP4.5 (left) and RCP8.5 (right), without (top) and with (bottom) adaptation of dike heights. Each line represents a different GCM-RCM combination from the EURO-CORDEX ensemble. (For details, see Dottori et al., 2021). Note that the domain in this figure is limited to EU-member states + UK, whereas Figure 2.5.11-13 included more European countries. This explains the somewhat lower baseline values in this figure, compared to Figure 2.5.11-13.

The new object-based approach developed for COACCH has an important benefit over the traditional grid-based approaches because it explicitly shows which road segments are the most vulnerable to flood hazards. Moreover, because the graph network properties of the road network are maintained, the flood information can be combined with an analysis of the criticality of road segments. This enables an assessment of flood events on the overall performance of the road network as presented in the next section. Besides the adaptation by dike heightening measures discussed above, this also offers another perspective of action to road operators. For example, they may elevate or flood-

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proof the most vulnerable parts of the highway network. In Box 11, we illustrate this action perspective for a COACCH stakeholder: the Dutch road operator Rijkswaterstaat.

Part II: Policy aiming at reducing risk of systemic road network failure or tipping points
Deliverable 3.4, section 2.6, explored if and under what conditions river floods may cause large systemic failure of road networks, or socio-economic tipping points. This looked at three different stakeholder perspectives and corresponding scales/levels of analysis.

The level 1 assessment took a pan-European perspective, and mutually compared the robustness of road networks of European countries against river floods and assessed their vulnerability to tipping points. We found that the risk of system-wide failures is relatively small, but that each country has its weak spots. Floods in these spots have a large impact on the functioning of the road network.

One important finding is that large differences in the robustness of national road networks against tipping points were observed. For example, Figure 2.4.15 shows that the road network of Albania is much more likely to experience a tipping-point like disruption than the road network of Belgium. For example, the left-hand panel shows that only a few small simultaneous floods (called micro-floods) may already disrupt 40% of the preferred routes between NUTS-3 regions in Albania, whereas the same degree of disruption in Belgium is only reached for a large number of micro-floods, which is much less likely to happen. The difference between Albania and the other countries is even more clear in the right-hand panel, which shows that in Albania some regions may readily become disconnected from other regions in case of a flood event. This can be explained from the topography of the network of the country, as shown in Figure 2.4.16. The western part of the country is relatively flat and hosts an important North-South corridor. The eastern part of the country is mountainous, and heavily relies on the western North-South corridor for long-distance trips. As a consequence, a small flood that hits a critical segment in the North-West corridor may disrupt up till 40% of the preferred routes in the country.

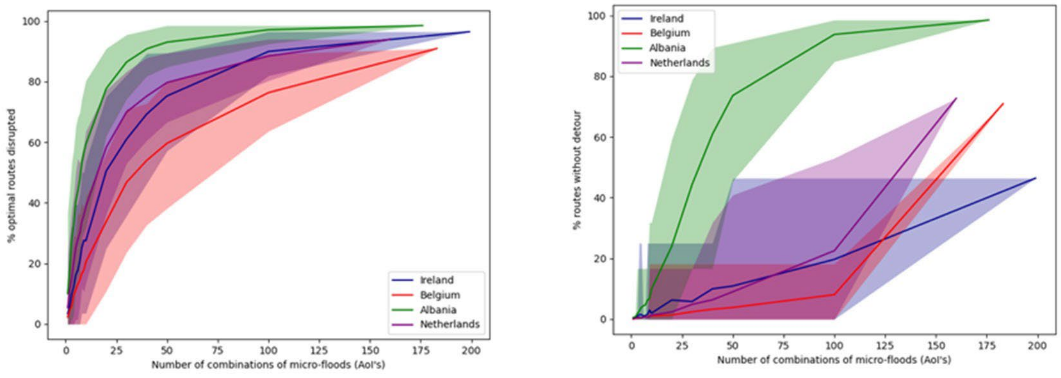

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Figure 2.5.15: Probability of large-scale malfunction of the national road network of some of the smaller countries in Europe. The left-hand panel shows the percentage of preferred routes between NUTS-3 regions (y-axis) that are disrupted by a certain amount of micro-floods (x-axis) at the same time. The right-hand shows the percentage of NUTS-3 regions which are no longer connected for a certain amount of micro-floods at the same time.

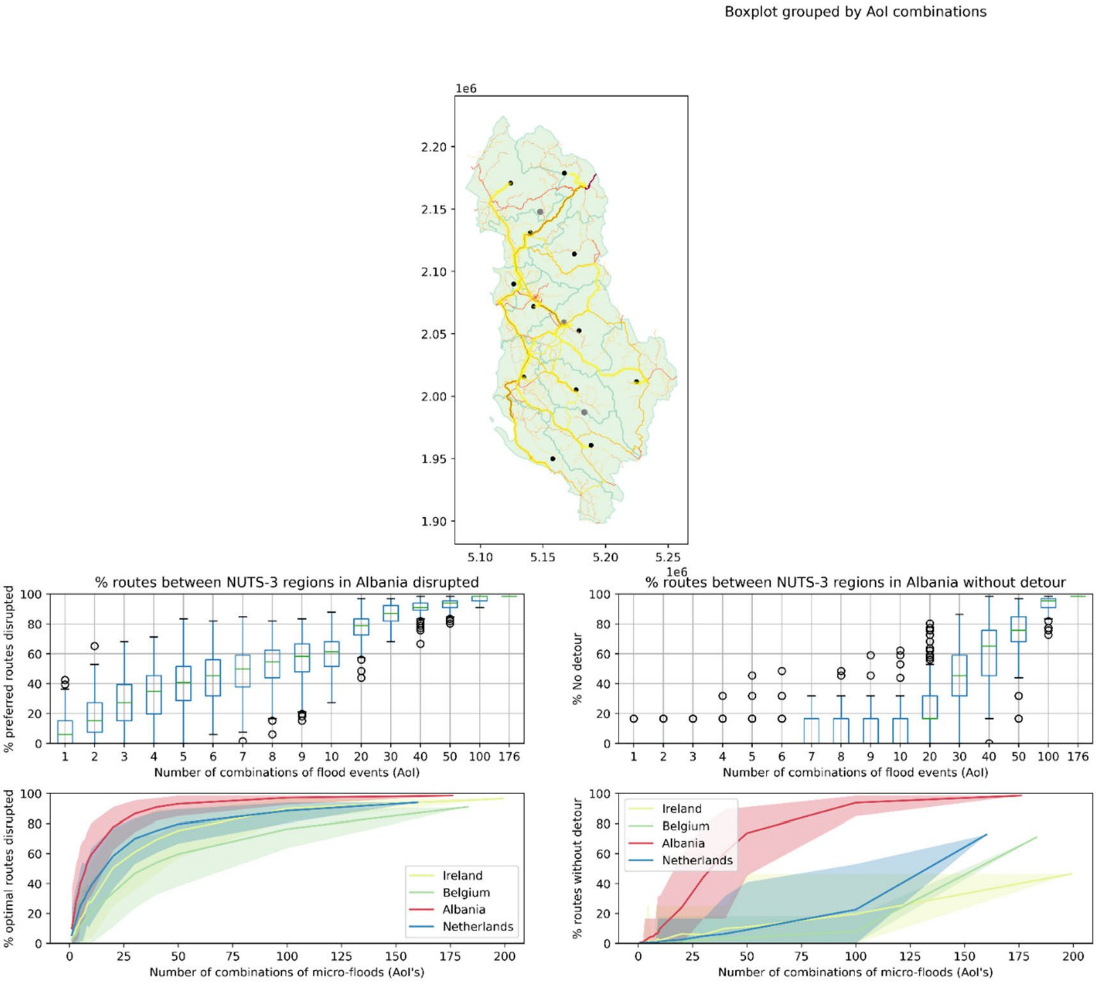

Figure 2.5.16: The robustness of Albania's road network against large-scale systemic malfunction. The top map shows the main road infrastructure, the yellow shading indicates how frequent the roads are used as the preferred route between NUTS-3 regions. The boundaries of the NUTS-3 regions are displayed in green, the black dots represent their centres.

The level 2 assessment took the perspective of the Austrian road operator and assessed river floods impacts on actual traffic flows and valued the economic consequences of plausible combinations of river floods (Deliverable 3.4, section 2.6). For a selection of relatively disruptive, but plausible floods, we evaluated the indirect economic losses by calculating the costs of delayed and cancelled trips. For this the Austrian traffic model, VMÖ 2025+, was run by the company TRAFFIX. We found that the most disruptive floods

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may cause damage in the order of € 100 million euro per event. This is a substantial amount of damage, but not so large that it can be expected to cause a large socio-economic shock. Nevertheless, the identified flood hotspots may be reason for further investigation and dialogue among road owners, traffic managers and regional and national policy makers, see Box 4 for a suggestion as to how these may be taken along in a policy process.

Box 4: An object-based approach to inform a risk dialogue

The new object-based approach was used to support a policy dialogue in a follow-up study for COACCH stakeholder Rijkswaterstaat, which is the Dutch road operator and part of the Dutch Ministry of Infrastructure and Water.

The study (de Grave et al., 2020) used the COACCH object-based approach to calculate direct infrastructural damage (repair costs of roads) and more indirect losses from additional travel time during flood events. It used the damage functions developed during the codesign process with the stakeholders in COACCH. The pan-European flood hazard maps were replaced with high-resolution maps of The Netherlands. These were available per single flood event (rather than an aggregated flood risk map for entire Europe), which enabled a coherent assessment of direct damage and traffic disruption per flood scenario. Instead of the large-scale river floods in COACCH, the focus was on failure of smaller scale local water systems with a higher likelihood, but smaller consequences.

Currently, the results are used in risk dialogues with experts responsible for the operation and maintenance of the national highway network. Because in the object-based approach the damage can be traced back to individual road segments, the road operators can discuss for each road segment if the climate risk is still tolerable, or whether action should be taken. In some cases, adaptation can be mainstreamed in regular maintenance cycles, which can strongly reduce the costs of adaptation.

The level 3 assessment took the perspective of one particular company: a car and truck manufacturer, which relies heavily on just-in-time deliveries to sustain a continuous production process. Instead of sampling random (as in level 1) or the most plausible (as in level 2) floods, we here iteratively sampled towards the worst-case flood for the supply chain of the factory. We found that at some point, driving times from suppliers to the manufacturer may exceed legal driving time constraints, which can lead to a strong non-linear increase of travel time and, without deviation from current practices and rules, a disruption of the production process. However, we also found that the risk that the car manufacturing site - or one of the supplying factories – itself would flood, is much more substantial than the risk that the transport connection between the two would be disrupted. The policy implications for companies, especially those depending on just in time deliveries, could be to review the flood vulnerability of their suppliers and supply routes using the simple methods developed in COACCH and consequently act on reducing the vulnerability of locations, increasing stocks etc.

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○ 2.6. Policy effectiveness in non-market impacts: ecosystems and health for policy makers and research (Lead: PWA)

Introduction

The aim of this sub-task, as set out in the description of work (DOW), is to undertake a case study to evaluate alternative policy actions for mitigation and adaptation in non-market sectors (ecosystems and health). The DOW also sets out that this case study is to be co-developed with policy maker participants as part of the deep engagement activities.

This deep engagement case study has focused on UK stakeholders, working with the UK Climate Change Committee (the CCC) and the UK Department for Environment, Food and Rural Affairs (Defra). It has focused on the policy area of national risk assessment and national adaptation programming. It has provided policy analysis to support the UK's 3rd Climate Change Risk Assessment (CCRA3) in the areas of ecosystems and health.

The UK Climate Change Act 2008 set out in law a requirement to undertake Climate Change Risk Assessment (CCRA) every five years, followed by a National Adaptation Programme (NAP). The objective is to consider current and future climate-related risks and opportunities to the UK, and the extent to which current or planned adaptation policies address these.

The UK CCRA is undertaken on a five-year rolling cycle and is now on its third cycle (CCRA3). The CCRA is an independent analysis, and informs the CCRA Advice Report, which is written by the UK's Climate Change Committee. The assessment is then used by the Government to provide a CCRA Government Report, which is laid before parliament. In turn, the CCRA informs the National Adaptation Programmes of England and the Devolved Administrations (DAs).

The priority for the CCRA Reports is, therefore, to identify potential risks and opportunities, and to help assess where action is needed in the next five years to manage climate change risks or opportunities that may arise over the short, medium and longer-term.

The CCRA3 uses a synthesis approach. It draws on a large body of peer-reviewed scientific literature and other quality-assured literature on climate change, risks and adaptation, complemented by new research studies in key areas.

The COACCH project has undertaken policy analysis to support CCRA3 in the areas of monetary valuation of climate change risks for the non-market sector, looking at different scenarios and thus providing information on the costs of inaction and the benefits of mitigation policy, as well as the costs and benefits of additional adaptation.

Method

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The method developed for CCRA3 (Watkiss and Betts, 2021) has drawn on the lessons that emerged from the second CCRA (CCRA2), published in 2017 (CCC, 2017), as well as from the evidence published in the IPCC Fifth Assessment Report (IPCC, 2014), and the latest climate science including the new UK Climate Projections (UKCP18). It has also drawn on developments in the academic literature as well as an increasing body of practical applications in climate change risk and adaptation assessment. This has led to a greater emphasis on an iterative risk management approach (adaptive management) and the framing of risks or opportunities so that they more directly inform potential adaptation decisions.

The approach uses an IPCC-like synthesis review to identify climate risk and opportunities at the national level. However, the synthesis information is collated and analysed using a particular method. In particular, the CCRA3 focuses on decisions or actions that could be made over the next few years, i.e. for the next adaptation programme period (2023-2027), noting that these will address risks in the short, medium and long-term. It also includes a more explicit assessment of the lifetime and the risk of lock-in associated with climate risks.

The methodology has been developed to provide consistent evidence across sectors and regions in ways that make it easier for the UK Government and the Devolved Administrations to respond, including where early interventions are needed to address risks (or opportunities). The aim is to provide a clear sense of where action is most urgently needed, and what form this might take, over the next five- year period.

The CCRA3 Evidence method is based on the prioritisation of risks and opportunities using an analysis of urgency. This seeks to identify where action is most urgently needed over the next five-year period using three questions:

1. What is the current and future level of risk/opportunity?

2. Is the risk/opportunity being managed, based on government commitments and other adaptation actions?

3. Are there benefits to further action in the next five years, over and above that already planned?

These three questions are shown within the decision flow diagram in the figure.

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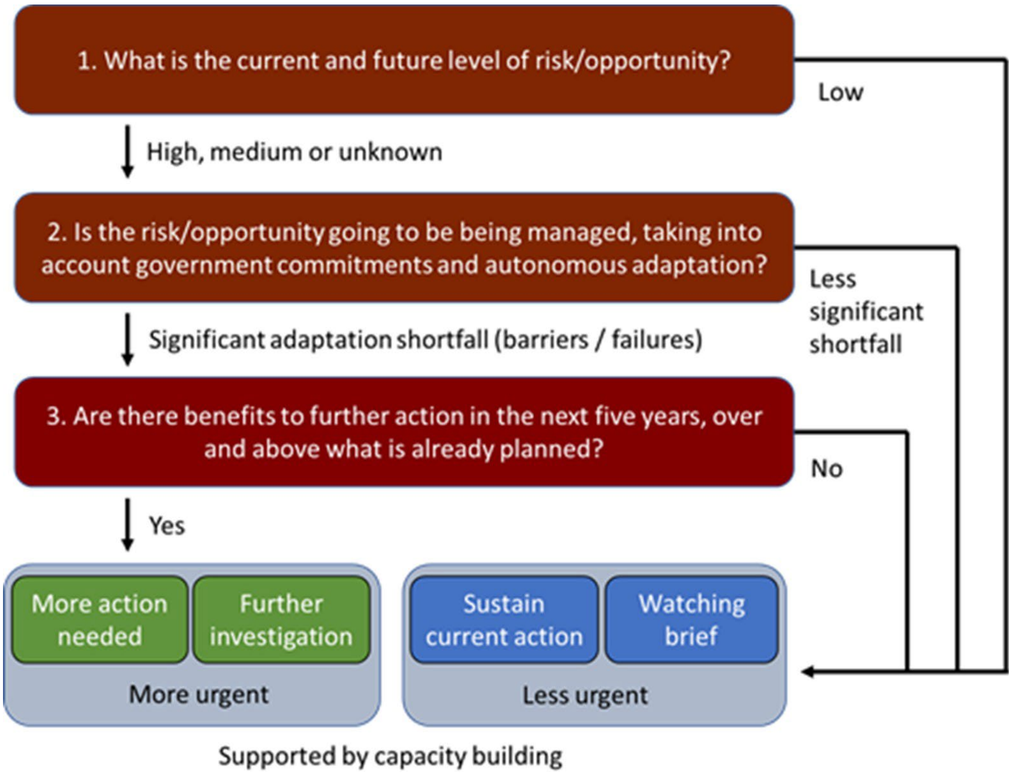

Figure 2.6.1: Urgency Scoring Framework.

For question 1, the analysis considers different future global warming scenarios, focusing on those associated with a 2°C and a 4°C increase in global mean temperature by the end of the century, relative to pre-industrial. It assesses the magnitude of risks for these scenarios, either in terms of their economic magnitude (shown below) or using other non-monetary criteria.

Table 2.6.1: Magnitude Score – Economic Categories.

High Magnitude	**Medium Magnitude**	**Low Magnitude**
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,	-£tens of millions damage (economic) or foregone opportunities,	-Less than £10 million damage (economic) or foregone opportunities,

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The economic valuation component – the focus of this COACH case study – is centred on question 1, and helps to inform this prioritisation of risks.

For the third of CCRA method steps, the CCRA3 uses a complementary framework to help to identify adaptation priorities, as well as what type of additional action could be useful. This approach builds on a well-established literature for identifying early adaptation priorities that has advanced a portfolio or 'building block' approach. This is centred on an adaptive management process and draws on the earlier work of Fankhauser et al. (1999); Ranger et al. (2010); Watkiss and Hunt (2011). This aims to identify three types of early adaptation priorities that can help address risks and opportunities within the next five-years:

- To address any current adaptation gap by implementing 'no-regret' or 'low-regret' actions that reduce risks associated with current climate variability, as well as building future climate resilience.
- To intervene early to ensure that adaptation is considered in near-term decisions that have long lifetimes and therefore reduce the risk of 'lock-in', such as for major infrastructure or land-use developments.
- To fast-track early adaptive management activities, especially for decisions that have long lead times or involve major future change. This can enhance learning and allows the use of evidence in forthcoming future decisions.

These three priorities are not mutually exclusive, and a combination of all three is often needed as part of a portfolio at the national level. These early priorities are shown in the adaptation priority framework below, following the timing of risk and the decision characteristics involved.

The COACH case study work has also provided inputs to question 3, providing supporting information on the costs and benefits of further adaptation action.

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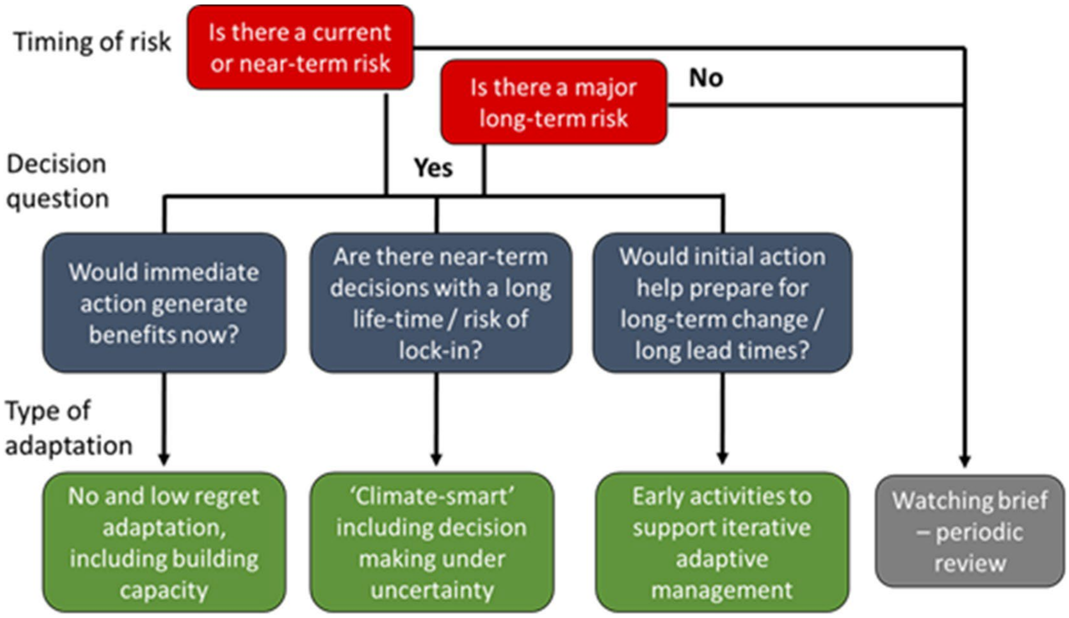

Figure 2.6.2: Early adaptation priority framework in CCRA3

At the end of the three CCRA3 steps, based on the evidence, each risk or opportunity is ranked into one of four urgency scores: i) "more action needed"; ii) "further investigation"; iii) "sustain current action"; or iv) "watching brief".

Results

CCRA3 identified over 60 risks and opportunities for consideration using this method. These were grouped in five thematic areas, including a theme on Natural environment and a theme on Health, Communities and the Built Environment.

The COACCH study undertook a monetary valuation – using a synthesis approach and the CCRA3 method - for the Natural Environment and Health sections. These fed directly into the CCRA3 analysis, published in June 2021 (UoE, 201), and a supporting valuation report (Watkiss et al., 2021).

Results natural environment valuation

For the natural environment, the risks and opportunities considered are presented below:

Table 2.5.2: UK CCRA Biodiversity Risks

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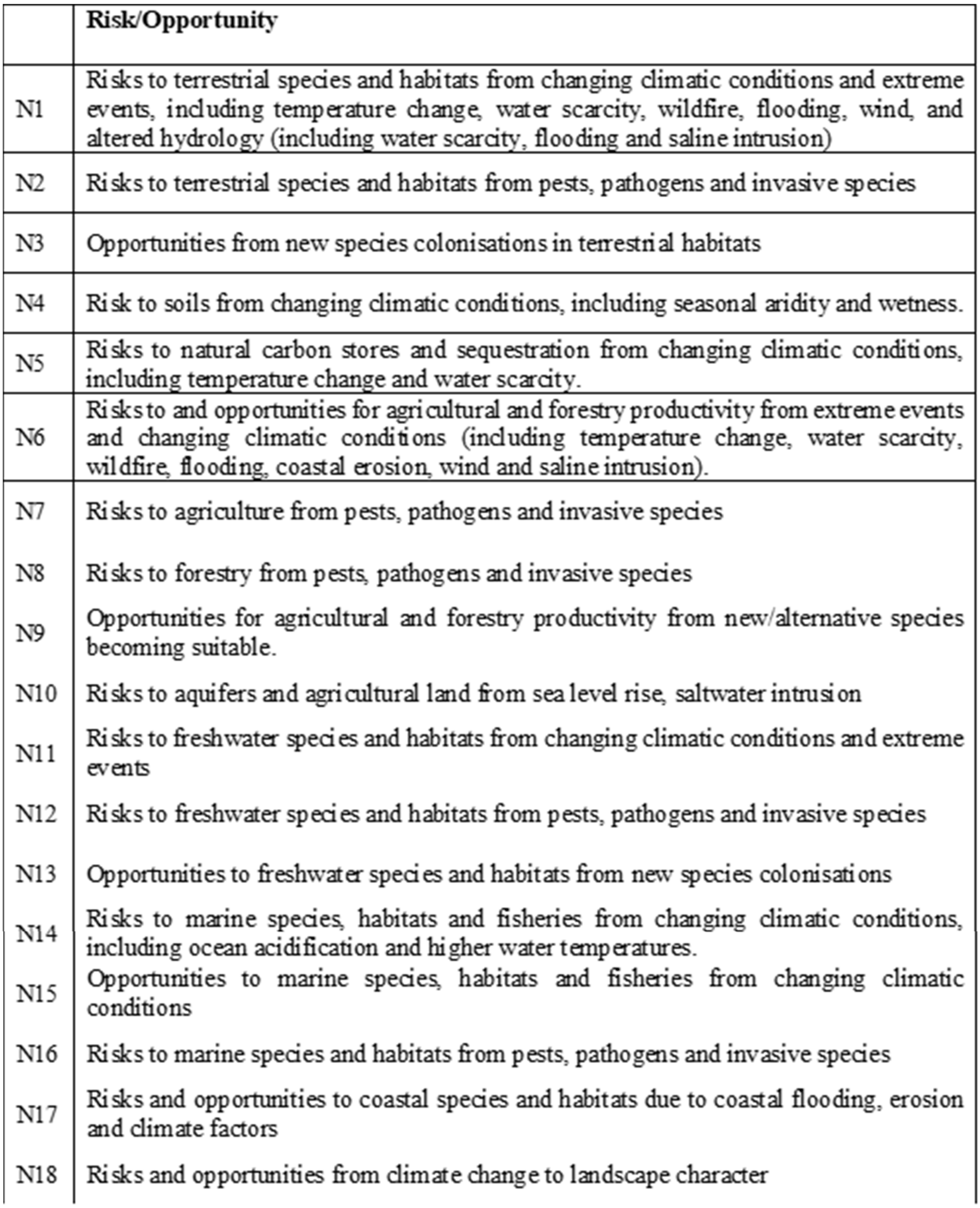

	Risk/Opportunity
N1	Risks to terrestrial species and habitats from changing climatic conditions and extreme events, including temperature change, water scarcity, wildfire, flooding, wind, and altered hydrology (including water scarcity, flooding and saline intrusion)
N2	Risks to terrestrial species and 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
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 challenging. 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 the natural environment relies on a mix of qualitative and semi-quantitative evidence, case studies, and expert judgement. Valuation is also challenging because the majority of the

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risks are not captured by market prices. Consequently, non-market measures of the willingness to pay to avoid impacts – or for positive impacts – are often 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). 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), and through valuation databases internationally (the Environmental Valuation Reference Inventory, EVRI) and in the UK (the Natural Environment Valuation Online tool (NEVO) as well as the Defra ENCA and the Natural Capital Accounts developed by the ONS.

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.

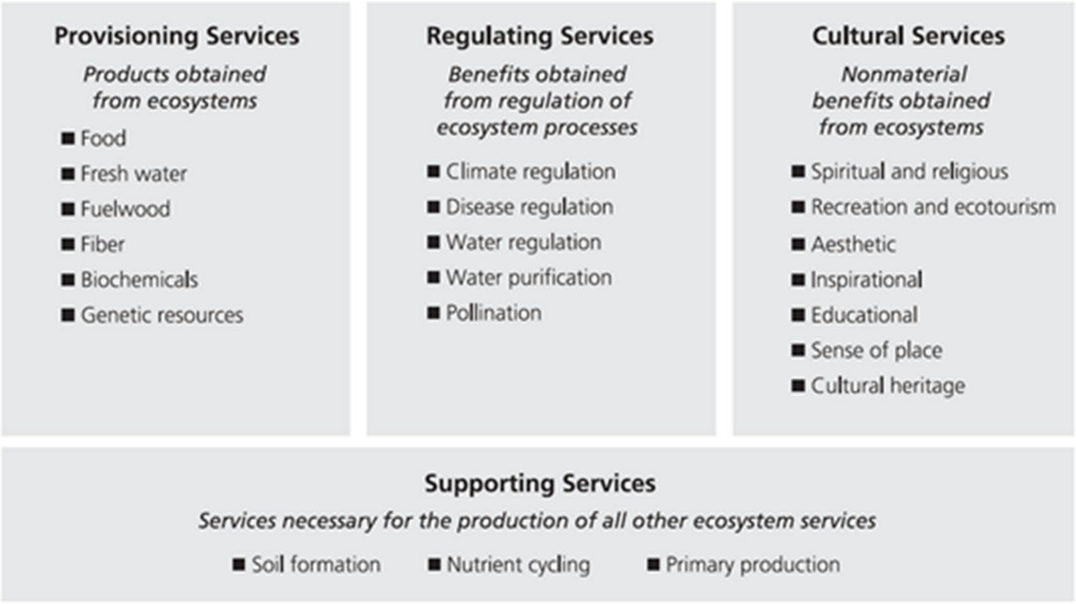

Figure 2.6.3: Ecosystem Services. Source Millennium Ecosystem Assessment.

For the valuation, the approach used was 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

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on the approach of Hooper et al. (2014) 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

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. 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 (Vanbergen et al., 2014). 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). 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.

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) 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

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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) 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). 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) 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) 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.

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) 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

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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.

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

N2 involves potential risks to regulating, provisioning and cultural services. This risk category 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.

N3 Opportunities from new species colonisations in terrestrial habitats

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 impact information, and the link to services.

N4 Risk to soils from changing climatic conditions,

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):

- Soil degradation (although this can include multiple processes, including those below);
- Soil erosion (from heavy precipitation and extremes);

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- 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.

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. The UK Government has a long tradition of using carbon prices in policy appraisal, going back almost two decades (See Watkiss and Hope, 2011). 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), which are used in this analysis.

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) 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

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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 GHGemission 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.

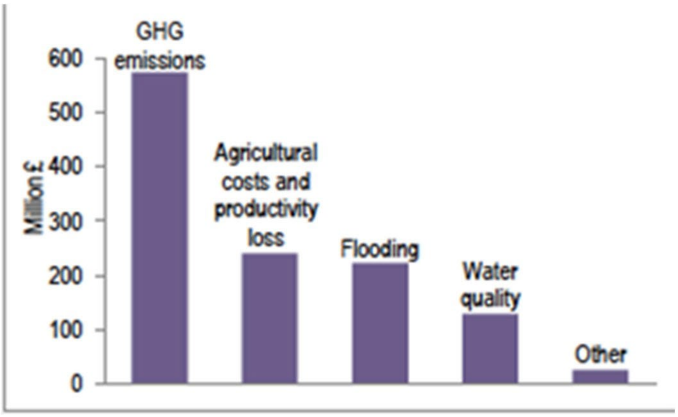

Figure 2.6.4: Annual costs of soil degradation in England & Wales. Source: POST, 2015).

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 presents estimates of the yield losses, and their value, associated with soil erosion. Their

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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 Graves 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^{o}C total costs are less than the 2^{o}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^{o}C scenario later this century than in the 2^{o}C scenario.

Table 2.6.3: 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 sometimes lead to benefits downstream).

Interestingly, there is a study (GFSP, 2017) 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.

N5 Risks to natural carbon stores and sequestration

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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). Applying the carbon values given in national appraisal guidance in the UK, 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 UKcroplands 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.

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)) provided estimates of the land cover in the year 2060, based on various socio-economic scenarios. AECOM (2015) 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.

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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 2.6.4: Present Value of soil carbon stocks from 2010 to 2060 (€ billion, 2019 prices, updated from original study using BEIS carbon values).

	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.

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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 found excess annual costs of €1.1 billion in the 2050s and between €1.5 billion and €2.2 billion in the 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. 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). 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 (toit) and may indeed be able to self-adapt (e.g. through changing their vegetation speciesmix) to continue functioning. The difference in impacts between 2°C and 4°C pathwaysis difficult to specify, but it is presumed that degradation risks and rates of degradationincrease with temperature and that trigger points, such as prolonged droughts or simplymore variable patterns of precipitation, may well exist for abrupt shifts in vegetation cover and erosion (see Moxey, 2019). 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 additionalon-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 slightly 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). Evans et al. (2016) estimate current annual emissions for English peatlands as around 11mt CO_{2e}. If published non-traded central carbon values and the standard 3.5% discount rate are applied to these, the implied Present Value costs to 2040 are around

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€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), costs would rise to between €14.5bn and €16.2bn respectively.

These 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).

N6 Risks to and opportunities for agricultural and forestry productivity from extreme events and changing climatic conditions

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

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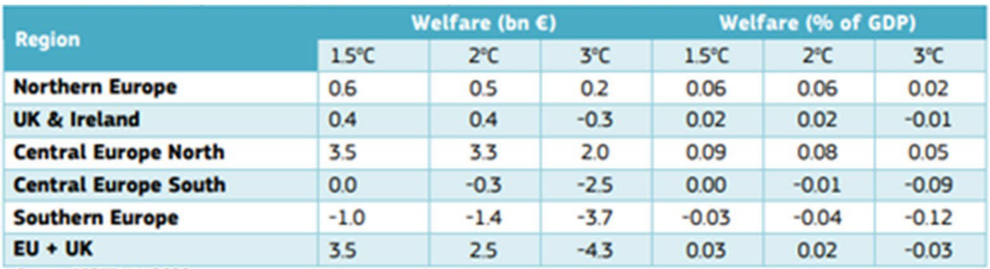
results can change further again when the consideration of reactive farm adaptation is considered. This means it is possible to find studies that cover the entire range from large negative to high positive outcomes for the UK. This study has reviewed some of the economic literature, focusing on studies 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) 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) 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 2.6.5: Change in welfare (bn €) from crop productivity change for the EU regions for the three climate scenarios. The reported changes are with respect to the 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.

Balkovic et al. (2015) 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

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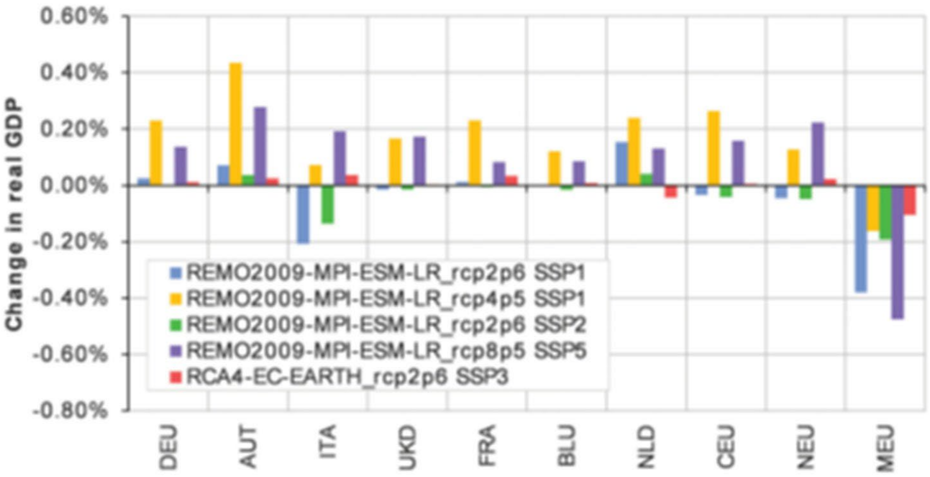
identified large uncertainties, partly due to the estimation on yield impacts, and the damage estimation was directly related to the production losses estimated using crop models, which in turn was directly dependent on assumptions on rainfall and precipitation patterns estimated using climate models.

The COACCH project (2020) 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 2.6.5: 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

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review the potential effects in the UK (Wreford et al., 2020), 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 the 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. 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. Additional impacts can arise from changes in forest ecosystem health, and from increasing forest fires, affecting managed and natural forests.

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Hanewinkel et al. (2013) 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.

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 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) 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) looked at wildfires across Europe by country, and projects increasing fires for the UK but did not monetise these.

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.

N7 Risks to agriculture from pests, pathogens and invasive species

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) 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) estimate that there is a loss equivalent to a cost of €250 per hectare, based on a grain price of €150/tonne

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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)), 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) 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) 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. 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). 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. 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 2.6.6: Cost of BTV Outbreaks under Climate Scenarios – England & Wales

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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 millionfor 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)). 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). Bradshaw et al. (2019) 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

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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) 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. Under the 2^{o}C scenario, monetary losses increase to €97 m per year while under the 4^{o}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^{o}C and 4^{o}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^{o}C scenario.

Table 2.6.7: Annual economic losses in lamb production by region. Average over a ten year period for baseline (2001 – 2010), 2^{o}C and 4^{o}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**

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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) 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.

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.

N8 Risks to forestry from pests, pathogens and invasive species

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). 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), as these conditions are projected by UKCP18. The primary cost of

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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). 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). 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 daysof 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 changeis projected to result in growing conditions more conducive to larch - 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 thatare 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 the number of tree cases under alternative climate scenarios.

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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), of which €22 million is commercial value of wood; the contributions of other ecosystem services are not stated. Goberville et al. (2016) 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

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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), 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 2.6.8: 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

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

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

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generates €8.5 billion of gross value added (NFU, (2017)) 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). This found that climate change could 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.

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

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.

N11 Risks to freshwater species and habitats from changing climatic conditions and extreme events.

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

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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), 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) 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 non polluted 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 2.6.9: 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.

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	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 €350million annually in England and Wales (Environment Agency, 2009). Any sizable impact on these species from climate change would therefore be expected to be equivalent toa “High” negative valuation rating.

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

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) suggests 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).

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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) 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 was 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) 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.

N13 Opportunities to freshwater species and habitats from new species colonisations

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.

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

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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.

N14. Risks to marine species, habitats and fisheries from changing climatic conditions

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), extreme temperature events are also important (Smale et al., 2019). 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) and climate change could also have impacts on fishing activities (distance travelled) and safety at sea (marine storms) (Woolf et al, 2013). 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.

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) in the UK. There are also likely to be impacts on fishing fleets: distance travelled, catch type, and values of catch (Frontier, 2013). 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) 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). Stock biomass is 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.

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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.

Table 2.6.10: 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**

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There are a number of other studies. Using cost-benefit analysis, Mangi et al. (2018) 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. InScotland, losses under the high scenario are greater – up to €2.5 billion, whilst in Walesand Northern Ireland they are both approximately €0.5 billion.

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 away 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.

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.

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

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

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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).

The potential opportunities are outlined in the previous risk: there are some potential species for which positive gains are expected. Jones et al. (2013) used the estimates from three species distribution models for 14 commercial fish in the Northeast Atlanticto 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 tomigration. Second, the potential economic benefits from the comparative advantage ofUK 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

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 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 it 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.

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

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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.

Sayers et al (2020) estimated coastal flood to designated areas. 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 2.6.11: 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) and European estimates of losses from climate change (Brown et al., 2011). The latter study suggests that 35% of

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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.

N18. Risks and opportunities from climate change to landscape character

Future changes to landscape character will occur from a range of natural responses to a change in climate including biodiversity, soils, hydrological processes and coastal processes. 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). However, it is not possible to apply these, as the risk assessment finds that quantification of climate change effects has not yet been undertaken.

Results Adaptation Costs and Benefits for Natural Environment

This section provides the synthesis of the costs and benefits of further adaptation action to address the risks above. This feeds into Step 3 of the CCRA methodology.

N1 Risks to terrestrial species and habitats

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

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

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

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pests and pathogens Phytophthora ramorum, Ash dieback, Dothistroma Red needle blight and Septora, a winter wheat yellowing fungus (see Watkiss et al., 2019). Although this would require additional Government action, Watkiss et al. (2019) project that the economic benefits are high compared with the costs. There is a clear role for public co-ordination of research, monitoring and surveillance. Previous analysis by SRUC (2013) has identified that investment in monitoring for pests has a high benefit-cost ratio of around 10:1. There are also clear benefits from the 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

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

N4 Risk to soils from changing climatic conditions

Research is now increasingly available on the cost effectiveness of different soil protection measures. Investments in soil monitoring would seem a low-regret adaptation and a necessary precursor for subsequent improvements. 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; Watkiss et al., 2019), indicating also the key role of policy support. For individual practices, measures are often highly site-specific, as reflected in large benefit-cost ratios for similar interventions in different places, and evidence on these practices as viable standalone adaptation strategies remains limited and sometimes contradictory depending on assumptions (e.g. relationship with other measures) and context. Posthumus et al. (2015), using an ecosystem services valuation approach, found that for soil erosion, use of tramline management, mulching, buffer strips, high-density planting and sediment traps were the most cost-effective control measures, with contour ploughing also cost-effective in some circumstances. However, the study also noted that assessments of effectiveness really need to be made at farm level or field level, because of the wide variation in biophysical and land use contexts, emphasising again the key role of outreach and guidance in stimulating proactive adaptation actions on the ground.

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

N5 Risks to natural carbon stores and sequestration

Restoration is a low regret action for degraded peatlands (CCC, 2013), with early action having short-term benefits as well as longer-term resilience to climate change. Moreover, early action is desirable given that restoration to a near-natural, fully-functional state can take decades or longer and that restoration costs increase with the degree of degradation faced. There has been some analysis on the costs and benefits of restoring peatlands and enhancing carbon storage (Moxey and Moran, 2014; Bright, 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). 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.

N6 Risks to and opportunities for agricultural and forestry productivity

There are a number of studies on costs and benefits of adaptation actions (Watkiss and Hunt, 2018), although their conclusions depend on the modelling approach (i.e. whether using farm level analysis, crop models, econometric analysis, or partial or general equilibrium models). Early studies using crop productivity models tend to identify

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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 analyze adaptation options including trade, shifting crop types and land-use expansion. These highlight important issues of market driven adaptation, and that changes that occur from impacts in the UK need to be seen in the European and even global context. Such studies (e.g. Hristov et al., 2020) report that large negative climate change impacts on productivity outside of the EU can lead to large market spill-over effects which could push up production in Northern Europe (including the UK, and assuming production capacity is available) as higher demand for some agricultural commodities outside of EU results in higher producer prices.

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

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

A report (CCC, 2018) examined how taking a long-term approach to considering the risks from climate change, and anticipating land-use changes to manage these risks, could deliver net benefits in terms of the maintenance of natural capital and the services it provides. An 'adaptation pathways' approach was used to develop understanding of

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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 the report.

Posthumus et al. (2015), using an ecosystem services valuation approach, found that for soil erosion, use of tramline management, mulching, buffer strips, high-density planting and sediment traps were the most cost-effective control measures, with contour ploughing also cost-effective in some circumstances. However, as above, the study also found that assessments of effectiveness really need to be made at farm level or field level, because of the wide variation in biophysical and land use contexts, emphasising again the key role of outreach and guidance in stimulating proactive adaptation actions on the ground. SRUC (2013) for the CCC also looked at soil management, considering six adaptations on a number of different crops. Under these assumptions, all the adaptations analysed (with one exception, for cover crops) generated positive NPVs. These did not require long lead times and had positive ancillary benefits, but the study still identified the challenge would be to encourage farmers to adopt them. All of this suggests that while sustainable soil management approaches have potential for reducing climate impacts, their uptake requires these barriers to be addressed, and may need a combination of awareness and incentives to realise (Watkiss et al., 2019) though there are obvious opportunities to provide additional incentives through revision of the current farm payment schemes.

Livestock adaptation options have been evaluated by Dittrich et al. (2017). The costs involved in adapting the farming system range from simple low- or no-cost to those requiring large investments of capital and labour (Wreford et al., 2015; Wreford and Topp, 2020). The lead-time and lifetime of that adaptation measure influence the choice of economic appraisal method used for the evaluation (Dittrich et al., 2017). In the case of short-term decisions that require a small investment or a reversible 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.

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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).

N7 Risks to agriculture from pests, pathogens and invasive species

N8 Risks to forestry from pests, pathogens and invasive species

The economic case for further uptake of existing adaptation measures is sound, as evidenced by case study analysis on pests and pathogens (Watkiss et al., 2019): it is much more effective to prevent introduction and establishment rather than attempt to mitigate spread and resulting impacts. However, this additional uptake of measures has an associated resource cost. There is a clear role for public co-ordination of monitoring and surveillance. Previous analysis by SRUC (2013) has identified that investment in monitoring for pests has a high benefit-cost ratio of around 10:1. There are also clear benefits from the 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.

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

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

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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

There are some studies which include the impacts (in economic terms) of climate change on saltwater intrusion (e.g. see Brown et al., 2011: Hinkel et al., 2014), but these tend to be aggregated alongside flood damages, and are low in comparison, and these studiesdo 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) 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

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), which include possible options that might have high relevance for addressing increasing climate related risks. There is also some information published by the EA (2019) as part of consultation, which highlights the need for an adaptive management approach to enhance the resilience of RBM plans.

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

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) 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

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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.

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

Options include 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 the 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).

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

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

N18 Risks and opportunities from climate change to landscape character

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

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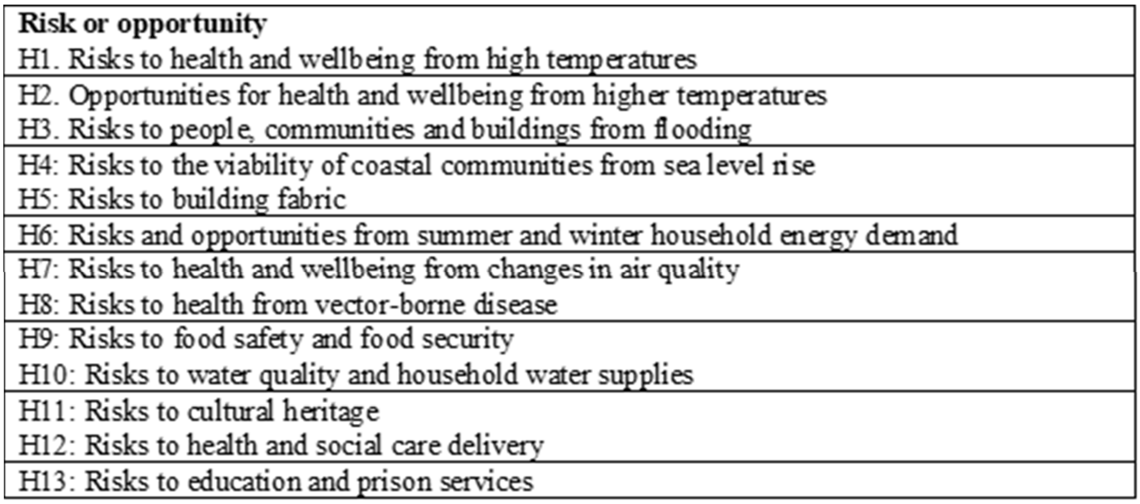
management. There are an existing set of measures for conservation, landscape restoration, etc. with cost estimates, but it is more difficult to assess the marginal actions needed to address climate change risks.

Results Health Monetary Valuation

The risks and opportunities considered in the CCRA3 Technical Report for Health, Communities and the Built Environment are shown below.

Table 2.6.12: UK CCRA Health, Communities and the Built Environment



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

The COACCH project focused on the valuation of the health related risks, thus H1, H2, H7, H8, H9 and H12.

H1. Risks to health and wellbeing from high temperatures

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) 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) 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: Kovats and Osborn., 2016).

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

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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 have been valued 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 of 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):

- 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). 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) 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) 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. This significantly increases future unit values, though it is stressed that the use of these

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economic costs (with uplifts) in subsequent policy analysis, such as adaptation cost-benefit analysis, should undertake discounting of future values (HMT, 2020), 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 casualties (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), with values of £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). 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).

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Table 2.6.13: 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			

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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). 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.

Table 2.6.14: 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

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) 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 the unit value of £700 per case, as used in the first UK Climate Change Risk Assessment (Hames

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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 a similar profile across the DAs to the mortality numbers.

Table 2.6.15: 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 is 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.

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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 demand 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).

H2. Opportunities for health and wellbeing from higher temperatures

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 infuture 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 2.6.16: 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.

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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

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) 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)). However, there is no information on how much climate change might increase recreation, to then allow the estimation of subsequent health benefits. If such

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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.

H7: Risks to health and wellbeing from changes in air quality

There is an established literature on the valuation of air pollution in the UK (Defra, 2020), 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, 2011) 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), 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.

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.

H8: Risks to health from vector-borne disease

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.

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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). 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. 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). 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) 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) 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 (attens of millions per year). This suggests that total costs in the UK might be similar if thedisease became widespread, e.g. which might plausibly in later years, although there iscurrently no evidence on the likelihood of this happening.

H9: Risks to food safety

There have been a number of studies on climate and food-borne disease, notably salmonellosis. Kovats et al (2011) 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.

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A latter study (IMPACT2C, 2015) estimated the resource costs of additional hospital admissions and additional cases of salmonellosis and campylobacteriosis at around €700 million in the 2041-2170 period for the A1B scenario for all of Europe. This would imply higher estimates (than the Kovats study above) for the UK.

H12: Risks to health and social care delivery

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).

Results Health Adaptation Costs and Benefits

This section provides the synthesis on the costs and benefits of further adaptation.

H1. Risks to health and wellbeing from high temperatures

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; Adaptation Sub-Commitee, 2014; Wood Plc (2019). 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

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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; Toloo et al, 2013). 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., (2016) 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; Bouwer et al., 2018; Chiabai et al., 2018). 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; Watkiss et al., 2019). 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)

H2. Opportunities for health and wellbeing from higher temperatures

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), 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.

H7: Risks to health and wellbeing from changes in air quality

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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) and the UK Clean Air Strategy (Defra, 2019) 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). 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

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). There are some estimates of impacts and studies of the WTP for vaccination against tick-borne encephalitis (Slunge, 2015), the cost-effectiveness for lyme disease (Hsai et al., 2002) and a cost-benefit analysis of TBE (Desjeux et al., 2005). 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

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). 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)), and these find the economic benefits could be significant if the current levels of infection are maintained or increased.

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H12: Risks to health and social care delivery

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: Gupta et al., 2016: PHE, 2018; Oikonomou et al., 2020). 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). 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.

For hospitals, there is some literature on hospital design (including retrofitting) that emphasis passive approaches (Giridharan et al., 2013: Fifield et al., 2018) 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.

Discussion

This case study has investigated the monetary valuation of various aspects of biodiversity that have been identified as being at risk from climate change in the UK. The findings are summarised in the table below. A number of key findings emerge fromthe analysis.

The focus of the valuation for the 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

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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.

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.

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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 too positively. This lack of evidence means that economic estimates of the impacts of climate change on the natural environment theme are only partial, i.e. a sub-total of the total effects of climate change. Nonetheless, even with the lack of evidence above, the size of impacts on the natural environment could potentially be extremely large, i.e. easily £billions/year and potentially tens of billions/year. There also appears to be a strong threshold level overall, with economic costs rising significantly for higher warming (4°C) scenarios. 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). Overall, 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.

Table 2.6.17: Economic Valuation of Risks and Opportunities for the Natural Environment.

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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
NE6. Risks to and opportunities for:					
Agriculture		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		M	M	H	Low
NE15. Opportunities to marine species, habitats and fisheries from changing climatic conditions		+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

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Key

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

The summary of the health, communities and built environment theme are presented below. 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).

There are very large monetary values associated with extreme heat (on health and well-being). At the same time, there are also very high benefits (opportunities) from the improvement in health and well-being from warmer temperatures, 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 affectthe same receptor, 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).

Table 2.6.18: Economic Valuation of Risks and Opportunities for Health, Communities and the Built Environment.

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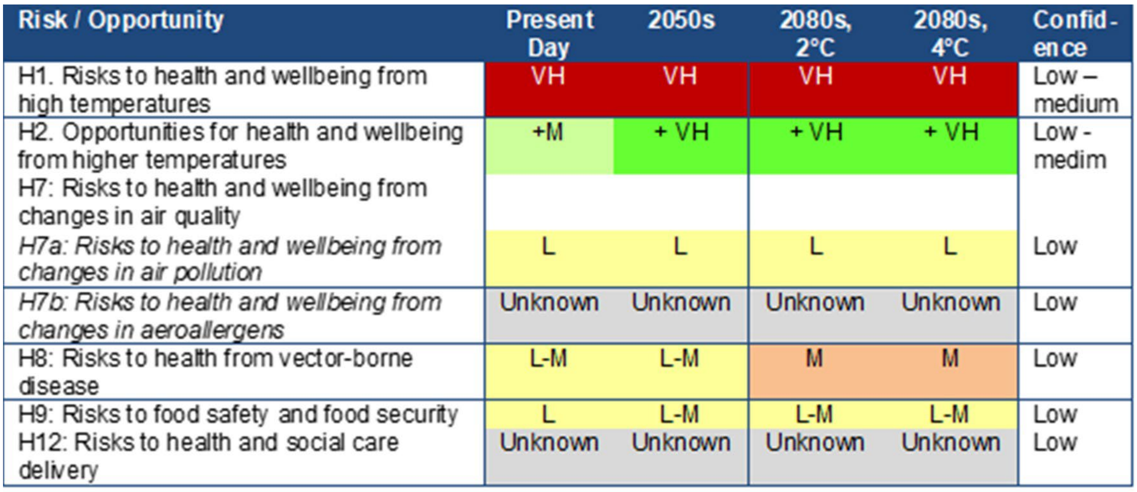
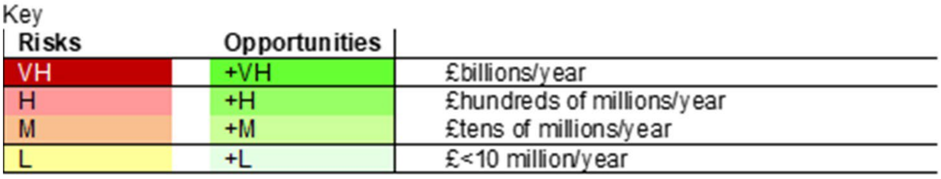


Risk / Opportunity	Present Day	2050s	2080s, 2°C	2080s, 4°C	Confid-ence
H1. Risks to health and wellbeing from high temperatures	VH	VH	VH	VH	Low – medium
H2. Opportunities for health and wellbeing from higher temperatures	+M	+ VH	+ VH	+ VH	Low - medim
H7: Risks to health and wellbeing from changes in 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
H12: Risks to health and social care delivery	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

The synthesis review of adaptation costs and benefits finds that the evidence is increasing, but is still partial. There is much more economic evidence for hard, technical options (e.g. building design to reduce over-heating risks), although there is now considerable literature on some soft options, notably around weather and climate services.

Where evidence exists, this indicates that there are potential adaptation responses that have positive benefit to cost ratios. This creates a strong case for further intervention in National Adaptation Programming to scale-up adaptation. However, there remain important gaps, particularly for adaptation for the natural environment (outside of provisioning services).

○ 2.7 Policy effectiveness for policy makers (Lead: PWA)

The final sub-task of this deliverable presents results from each of the sectoral teams working in WPs 2 and 3, and assesses the potential effects of mitigation and adaptation policy for their sectoral modelling assessments. Where possible, this produces quantitative estimates of the costs and benefits of alternative policy actions, at the EU level. This information provides key inputs of relevance for European policy makers. These results have also been used to summarise the COACCH results in the sector policy brief.

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Method

The case study does not set out the detailed methods and approaches for each sector – these are included in the relevant deliverables in WP2 and 3. However, in some sectors, additional work was undertaken in this task to express results in monetary terms, or to assess various policy options. Where this additional analysis has been undertaken, method descriptions are included.

Results

The results are presented by sector below.

Coastal Zones

Coastal zones contain high population densities, significant economic activities and provide important ecosystem services. Climate change has the potential to increase risks to these coastal zones in the future, from a combination of sea level rise, storm surge and increasing wind speeds, which will lead in turn to flooding, loss of land, coastal erosion, salt water intrusion and impacts on coastal wetlands.

COACCH has assessed the potential impacts and economic costs of sea-level rise in Europe, and the costs and benefits of adaptation. To do this, the COACCH project has further developed the global integrated assessment model DIVA, to provide European and national estimates of the impacts of sea-level rise on coastal areas (see D2.3 Impacts on infrastructure, built environment, and transport) (Lincke et al., 2018).

The analysis has considered future climate and socio-economic change. As floods are probabilistic events, the results are presented as expected annual damage (EAD) costs (undiscounted).

The study estimates that, annually that the number of people flooded in the EU could range from 1.8 million (RCP2.6) to 2.9 million (RCP8.5) by the 2050s and, potentially, 4.7 million (RCP2.6) to 9.6 million (RCP8.5) by the 2080s, if there is no investment in adaptation.

This flooding, along with other impacts of sea- level rise (e.g. erosion), leads to high economic costs, shown below. The annual expected damage costs in Europe are estimated at €135 billion to €145 billion (mid estimates for RCP2.6 and RCP4.5 respectively for the 2050s (combined effects of climate and socio- economic change, based on current prices, with no discounting), rising to €450 billion to €650 billion by the 2080s. These costs include direct impacts and costs of land loss (with direct changes clearly dominating the overall cost by several orders of magnitude). Additional

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unquantified costs will occur due to ecosystem losses and possible knock-on effects of damage on supply chains. It is stressed that there is a wide range of uncertainty around these mid estimates, reflecting the underlying uncertainty in the sea- level response to a given emissions scenario and temperature outcome, and the role of ice sheet melt.

Table 2.7.1: European Coastal Damage Costs for Various RCP scenarios (no adaptation).

Coastal damage	**RCP2.6-SSP2**	**RCP4.5-SSP2**	**RCP8.5-SSP5**
2050s / mid century	€115-210 Bill/yr	€130-235 Bill/yr	€310 Bill/yr
2080s /end century	€365-795 Bill/yr	€510-1,200 Bill/yr	€2,400 Bill/yr

Values are presented as additional impacts relative to the baseline period, from the combination of climate and socio-economic change, and are presented as undiscounted values in future years in current prices.

These values provide information on the economic benefits of mitigation policy. It can be seen that the costs rise rapidly by the late century, notably for the high emission RCP8.5 scenario. The results show a disproportionate increase in costs for higher warming scenarios in the second half of the century under such scenarios. This highlights the benefits of mitigation strategies. There are large benefits in moving from a high emission scenario (RCP8.5) to a low emission scenario (RCP2.6) which is broadly consistent with the Paris Agreement of limiting temperature to well below 2°C above pre- industrial levels. For the late century (2080s) there are also large benefits in moving from the RCP4.5 to the RCP2.6 scenarios. Note that at mid-century (2050s), there is relatively little difference between these scenarios, because of the lag in the climate system and in sea-level rise response.

Importantly, there are major differences in the damage costs borne by different Member States, with strong distributional patterns across Europe. The greatest costs are projected to occur around the North Sea (Belgium, France, Netherlands, Germany and the UK) and some regions in Northern Italy, if no adaptation occurs. This is shown in the map of coastal damages.

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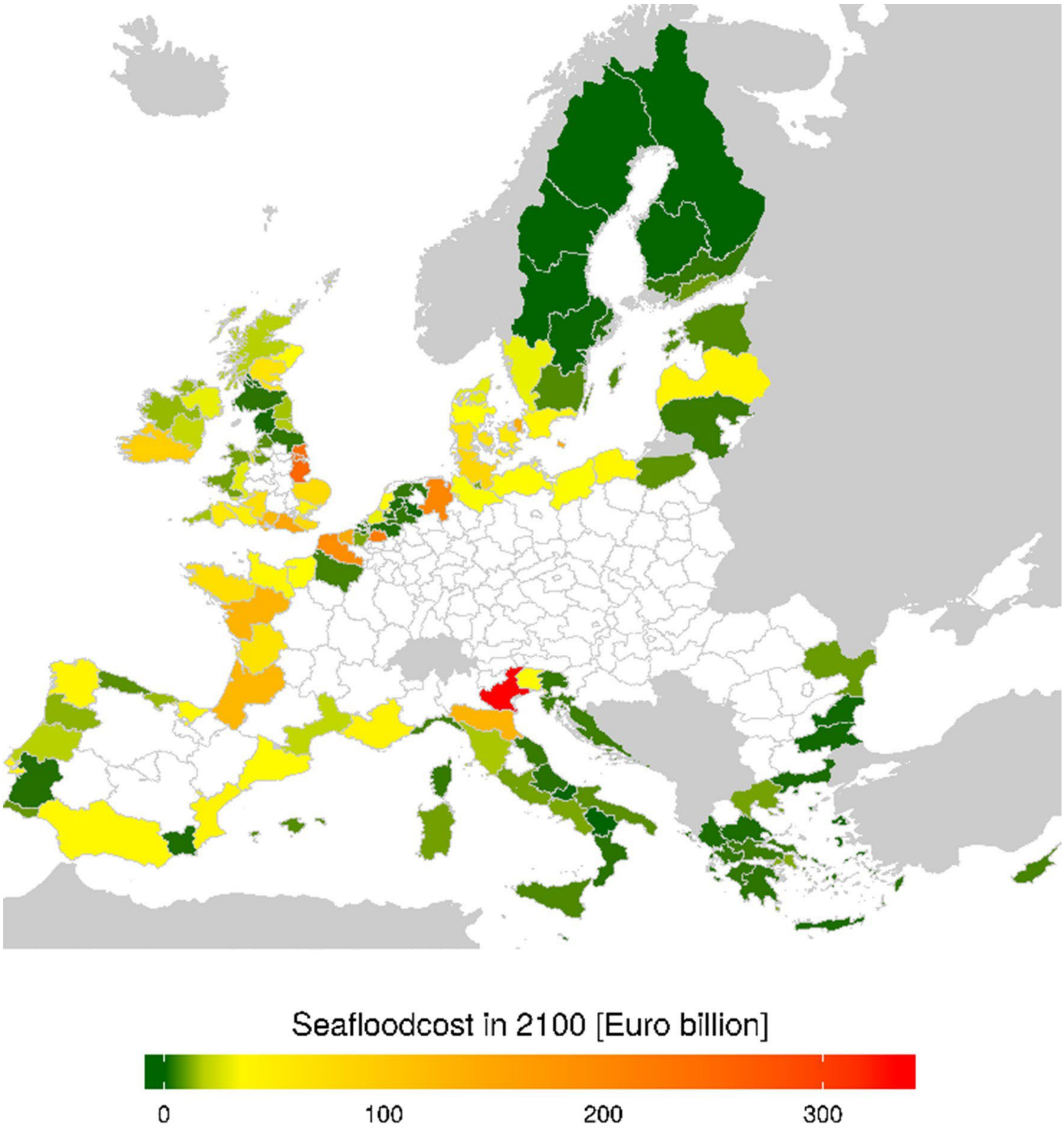

Figure 2.7.1: Map of European Coastal Flood Impact (no adaptation).

The COACCH analysis has also used the DIVA model to look at coastal adaptation and estimate potential costs and benefits. Adaptation can reduce the number of people flooded very significantly, for example, with adaptation, the number of people flooded annually would fall from several millions to around 230,000 – 290,000 in the 2050s.

Adaptation is also projected to significantly reduce damage costs. The analysis finds that adaptation is an extremely cost-effective response, with hard (dike building) and soft (beach nourishment) reducing impacts to very low levels, as shown in the table above.

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Subtracting the two scenarios (with and without adaptation), it can be seen that the economic benefits of adaptation are very large, estimated at €87-181 Bill /yr (RCP2.6) to €102-205 Bill /yr (RCP4.5) in the 2050s, and much larger than this under extreme SLR scenarios (RCP8.5), although some residual damage still remains even with adaptation.

However, this will require additional investment in adaptation, and hard defences need ongoing maintenance to operate efficiently and to keep risk at a low or acceptable level. Therefore the stock of coastal protection grows throughout the 21st century, as do annual maintenance costs. Adaptation to rising sea-level in Europe is projected to cost between 15 and 20 billion Euro every year by the mid-century, and much more than this later in the century under higher warming scenarios. Nonetheless, the benefit- to-cost ratios of coastal adaptation are very large, and increase throughout the century.

Table 2.7.2: European Coastal Damage Costs for Various RCP scenarios (with adaptation)

With Adaptation	RCP2.6-SSP2	RCP4.5-SSP2	RCP8.5-SSP5
2050s / mid century	€ 28-29 Bill /yr	€ 28-30 Bill/yr	44 Bill/yr
2080s /end century	€ 46-50 Bill /yr	€ 46-53 Bill/yr	110 Bill /yr

Table 2.7.3: Coastal adaptation costs €/yr

Coastal Adap. Cost	RCP2.6-SSP2	RCP4.5-SSP2	RCP8.5-SSP5
2050s / mid century	€14-16 Bill/yr	€15-17 Bill/yr	€17 Bill/yr
2080s / end century	€15-17 Bill/yr	€16-19 Bill/yr	€33 Bill/yr

Values are presented as additional impacts or costs relative to the baseline period, from the combination of climate and socio-economic change, and are presented as undiscounted values in future years in current prices.

It should be noted that these costs vary significantly with the level of future climate change, and the objectives and framing used for adaptation decisions, notably whether to plan for an acceptable level of risk protection or based on economic efficiency.

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Furthermore, there is a need to recognise and work with uncertainty – which requires an iterative and flexible approach for adaptation planning – noting that adaptation needs to be positioned within a broader integrated coastal-zone management policy framework.

These results reinforce the message that the most appropriate response to sea-level rise for coastal areas is a combination of adaptation to deal with the inevitable rise and mitigation to limit the long-term rise to a manageable level. More detailed, local-scale assessments are also required to assess and reduce risk to vulnerable areas, including adaptation plans.

River Floods

River floods are one of the most important weather-related loss events in Europe and have large economic impacts, as reported in recent severe flooding events. Climate change will intensify the hydrological cycle and increase the magnitude and frequency of intense precipitation events in many parts of Europe. 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.

The COACCH project has used the GLOFRIS model to assess the potential impacts of climate change on floods in Europe. As floods are probabilistic events, the results are presented as expected annual damage (EAD) costs (undiscounted) (see D2.3 Impacts on infrastructure, built environment, and transport) (Lincke et al., 2018).

The starting point for the analysis is to assess the levels of flooding, including the number of people flooded. This is shown below.

The annual expected damage costs in Europe (EU28) with climate change are projected to increase to approximately €12 billion by the 2050s (for the mid estimates for both RCP2.6 and RCP4.5), rising to approximately €20 billion by the 2080s. These estimates include the combined effects of climate and socio-economic change, and are based on current prices, with no discounting. It should be noted that the damages reported here only include direct physical losses and could, therefore, be conservative.

The costs rise rapidly in the late century, especially for higher emissions pathways, and estimated damages double for the RCP8.5-SSP5 scenario. This highlights the benefits of mitigation strategies, i.e. there are large economic benefits from moving from a high emission scenario (RCP8.5) to an ambitious mitigation scenario (RCP2.6).

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Table 2.7.4: European River Flood Damage Costs (EAD) for Various RCP scenarios (no adaptation).

Flood damage	**RCP2.6-SSP2**	**RCP4.5-SSP2**	**RCP8.5-SSP5**
2050s / mid century	€11 Bill/yr	€12 Bill/yr	€18 Bill/yr
2080s /end century	€18 Bill/yr	€20 Bill/yr	€42 Bill/yr

Values are presented as additional impacts relative to the baseline period, from the combination of climate and socio-economic change, and are presented as undiscounted values in future years in current prices.

The results show flood risks are distributed unequally over the EU28. River flood damages are higher for regions on the Iberian Peninsula, in the South of France, and in the North of Finland/ Sweden.

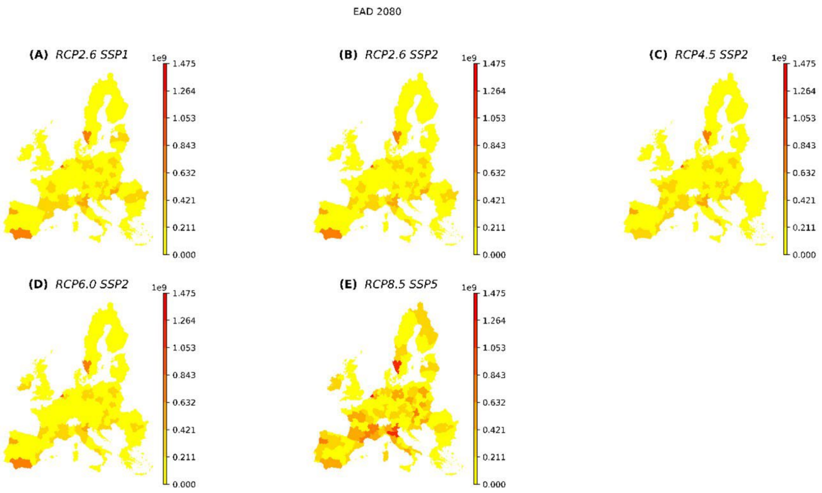

Figure 2.7.2: EU28 river flood cost (€) in 2080 on NUTS2 level for selected RCP/SSP combinations

It is stressed there is a very wide range around these central (mean) estimates, representing the range of results from different climate models. These differences are

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even more significant at the country level. This highlights the need to consider this variability (uncertainty) in formulating adaptation strategies.

The analysis has also assessed the potential costs and benefits of adaptation using the GLOFRIS model (Ignjacevic et al., 2020). This has assessed a scenario where optimal protection standards are determined based on a cost-benefit analysis. The results are shown below and demonstrate that adaptation is extremely cost-effective in reducing the damage costs above to low levels, and also has high benefit to cost ratios (Tiggeloven et al., 2020).

Subtracting the two scenarios (with and without adaptation), it can be seen that the economic benefits of adaptation are large, estimated at €6.4 Bill /yr (RCP2.6) to €6.9 Bill /yr (RCP4.5) in the 2050s, and much larger than this for the extreme scenario (RCP8.5). However, adaptation will involve significant investment over the century and thus high adaptation costs.

Table 2.7.5: European River Flood Damage Costs (EAD) for Various RCP scenarios (with adaptation).

With Adaptation	**RCP2.6-SSP2**	**RCP4.5-SSP2**	**RCP8.5-SSP5**
Optimal			
2050s / mid century	€4.6 Bill/yr	€4.7 Bill/yr	€7.7 Bill/yr
2080s /end century	€7.7 Bill/yr	€8.0 Bill/yr	€18.2 Bill/yr

Values are presented as additional impacts relative to the baseline period for the EU 28, from the combination of climate and socio-economic change, and are presented as undiscounted values in future years in current prices.

As with coastal adaptation, costs vary significantly with the level of future climate change, and as shown above, with the objectives and framing used for adaptation decisions. Furthermore, there is a need to recognise and work with uncertainty, and to progress detailed, local scale assessments.

Transport

The risks of climate change for the transport sector primarily arise from extreme events, such as flooding, heat waves, droughts and storms, especially where these exceed the

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design range. As well as direct damage costs to infrastructure, these extremes have economic costs from passenger and freight transport disruption (travel time) and accidents. There are also wider indirect effects from transport disruption, affecting the supply of goods and services, which can be significant for major events.

For the COACCH project, a new continental scale flood risk model was developed on European road infrastructure, OSdaMage. The primary focus was on impacts from river flooding. Expected annual damage (EAD) was calculated for direct damage to road infrastructure in the EU28 (see D2.3 Impacts on infrastructure, built environment, and transport) (Lincke et al., 2018). The baseline analysis identified direct costs of ~€200 million per year.

These damages increase under climate change. The values are shown below for the combination of climate and socio-economic change (no discounting, no adaptation). It can be seen that in the late century, there are much higher damages under the high emission RCP8.5 scenario.

Table 2.7.6: European Flood Impacts on Transport (direct only) for EU28 for various RCP scenarios (no adaptation).

		RCP4.5-SSP2	**RCP8.5-SSP5**
2050s / mid century		€954 M/yr	€1147 M/yr
2080s /end century		€1469 M/yr	€2286 M/yr

Values are presented as additional impacts relative to the baseline period, from the combination of climate and socio-economic change, and are presented as undiscounted values in future years in current prices.

The spatial distribution of damages under climate change is presented in the figure. This shows Germany, France and Italy exposed to the highest risks.

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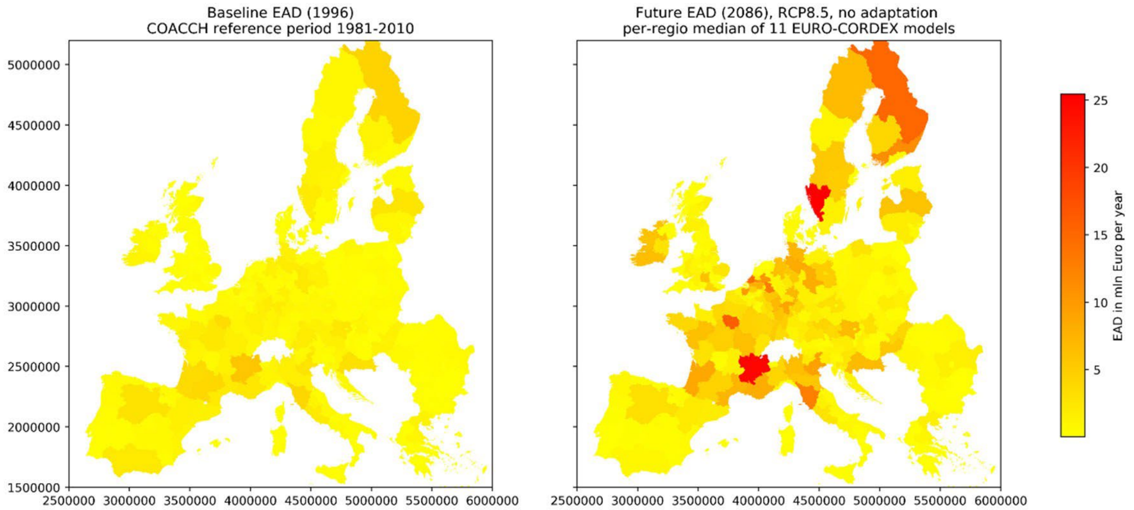

Figure 2.7.3: Expected annual damage (EAD) to road infrastructure in 1996 and 2086, aggregated on NUTS-2 level.

When river flood adaptation is included, as analysed in the earlier river flood section, the damages to the transport sector are also reduced significantly, shown in the table. Subtracting the two scenarios (with and without adaptation), it can be seen that the economic benefits of adaptation are large, estimated at €562 Mill /yr (RCP2.6) to €645 Mill /yr (RCP8.5) in the 2050s. However, as highlighted in the earlier section, this requires significant investment costs in river flood protection that will rise over the century.

Table 2.7.7: European Flood Impacts on Transport (Direct Impacts only) in Europe (with adaptation).

		RCP4.5-SSP2	**RCP8.5-SSP5**
2050s / mid century		€392 M/yr	€502 M/yr
2080s /end century		€592 M/yr	€888 M/yr

Values are presented as additional impacts relative to the baseline period, from the combination of climate and socio-economic change, and are presented as undiscounted values in future years in current prices.

Business and Industry

Climate change impacts such as floods, high temperatures, and water availability, will all impact business and industry. The balance of risks will vary with sub-sectors and locations, and sites and operations will be affected differently. Risks also extend along supply chains, with impacts in non-European countries affecting production and transport of raw materials and intermediate goods. There will also be shifts in demand for goods, services, and trade. All of these may affect business costs, profitability, competitiveness, employment and sector economic performance.

The COACCH project has developed new estimates of the impacts of climate change on the **industry and service** sectors using econometric analysis. It has combined (spatial) information on sectoral labour productivity (for different sectors) with high resolution meteorological data (sub- national) to investigate the impacts of changes in temperature and heatwaves (see D2.4 Impacts on Industry, Energy, Services, and Trade) (Schleypen et al., 2019).

The analysis has identified that the current optimal annual average temperature (productivity maximising) in the industry and construction sectors are 10.8°C and 10.0°C, respectively. The relationships are shown in the figure below. Interestingly, the study did not pick up large statistically significant effects for the services sector, although the results did indicate a higher optimum of 16.3°C. The optimal temperature for the services sectors is higher, as workers are not as exposed to outside temperatures, noting also that higher temperatures benefit the attractiveness of certain sectors, such as summer tourism.

The results show labour productivity falls at both relatively low and high temperatures, which are the result of various worker responses. The analysis also found significant negative direct impacts of temperature extremes on both industrial and construction labour productivity, suggesting that both higher average and extreme events (heat-waves) affect productivity.

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The analysis then looked at the future changes in labour productivity under climate change. The results estimate that climate change could reduce industrial labour productivity under the high-warming RCP 8.5 pathway by 4.3% and construction sector labour productivity by 6.6% by the late century (assuming the relationships above are constant over time). Under a more moderate warming scenario of RCP4.5, industrial and construction sector productivity will decline by 2.7% and 3.1%, respectively by the end of the century. This highlights the benefits of mitigation strategies. The results have a strong distributional pattern across Europe, as seen in the figure.

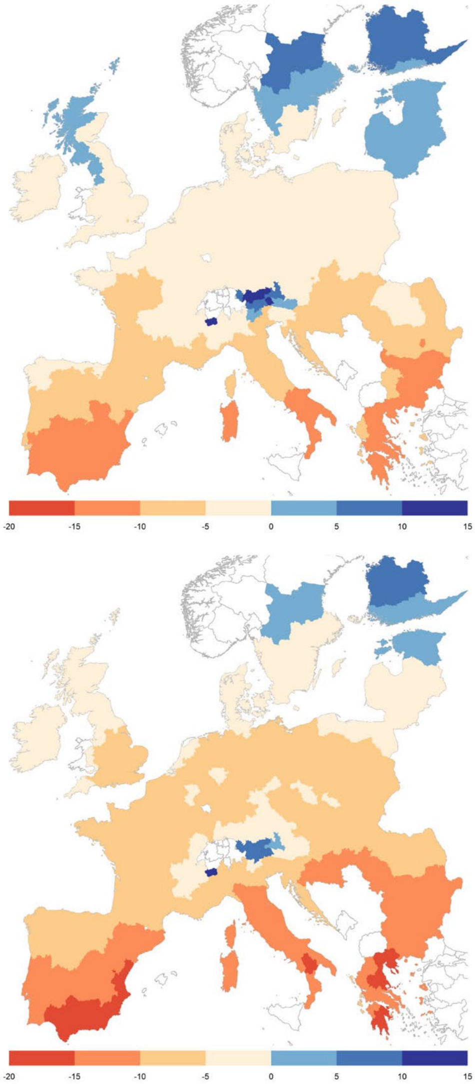

Figure 2.7.5: Percentage change in labour productivity due to climate change under RCP8.5 on industrial (top) and construction productivity (bottom) by 2070, compared to the reference period of 1985–2005.

The highest declines will occur in Greece (Peloponnese, Thessaly, and Attica), Italy (Puglia), Spain (Region of Murcia and Andalusia), and Portugal (Algarve). However, some colder regions in Austria, Estonia, Finland, Sweden, and the north-eastern and north-western Italian regions will gain.

COACCH has also undertaken new econometric analysis to investigate the impact of weather change on **tourism**. This has worked at the regional level across Europe (North, West, East, South, and Balkan). The analysis has assessed the effect of temperature and climate extremes on tourism in Europe during the summer months (June to September).

The effect of temperature was found to have an inverted U-shape form, reflecting the suitability range and optimum of the temperature-tourism relationship (see D2.4).

However, the threshold levels vary from region to region. The association between temperature and arrivals is not the same across the regions. In countries that are relatively cold (North), the effect of increasing temperature is always positive, increasing attractiveness. In other regions, increasing maximum temperatures generally have negative effects, and a particular issue was found for Southern Europe, which is very close to the thresholds associated with high impacts already. In EAST and WEST, an increase in maximum monthly temperature has a stronger effect than an increase in average temperature. Tourists coming to countries grouped in EAST are in particular sensitive to changes in average temperature beyond 35 °C. The project is now using these relationships to look at future climate change. In other regions, increasing maximum temperatures generally have negative effects, and a particular issue was found for Southern Europe, which is very close to the thresholds associated with high impacts already. The project is now using these relationships to look at future climate change.

Energy

Temperature is one of the major drivers of energy demand in Europe, affecting summer cooling and winter heating for residential properties and business/industry. Climate change will affect future energy demand, increasing summer cooling but reducing winter heating. These responses are largely autonomous and can be considered as an impact or an adaptation. Climate change will also have effects on energy supply, notably on hydro- electric generation, but also on wind, solar, biomass, and thermal power (nuclear and fossil).

COACCH has undertaken new econometric analysis to investigate the effects on wind energy. Results find that the wind load factor capacity over Europe is maximised at 10 m/s, above which generation declines. Air density also has a positive impact on load factor capacity, as increased air density exerts added pressure on the turbines, thereby increasing power generation.

These relationships have been applied to future climate change projections. Under the RCP4.5 projections, load factor capacity from wind power is projected to decline by 5.6% by 2050, and by 7.3% towards the end of the century. The biggest declines in load factor capacity due to changing wind patterns are projected for northern Austria, northeast Italy, and eastern Switzerland, with wind power generation projected to increase in parts of the United Kingdom and Ireland. These projected impacts are slightly higher than previous studies (Tobin et al. 2014). Under an unmitigated climate change scenario of RCP8.5, load factor capacity is projected to decline by 6.9% by 2050 increasing by

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2070 to 9.7%, with the highest decline in eastern and western Sweden, and in Andalusia, Spain.

COACCH has also modelled the projected changes in hydropower production in Europe and globally. Under a moderate warming scenario of RCP4.5, the highest declines will be in Finland (6.3%), Estonia (6.2%) and Serbia (5.9%), noting hydropower is a significant share of electricity production in each of these countries. These impacts increase by the end of the century, with large projected impacts (10%) estimated for Slovenia, Croatia and Austria. These impacts increase under high warming scenarios (RCP8.5) especially in the later part of the century. By the end of the century, for a high warming scenario, decreases in hydropower generation are estimated to be 13% in Serbia, Romania, Hungary and Sweden.

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 also from indirect effects, e.g. changes in the prevalence of pests and diseases. These will affect crop yields and, in turn, agricultural production, consumption, prices, trade and decision-making on land-use.

COACCH has developed new estimates of the costs of climate change on agriculture, derived from a suite of models to quantify. This uses a range of climate models, three crop models (EPIC, GEPIC and LPJmL 5) and two bio- economic models (MAgPIE 4 and GLOBIOM-EU) covering the land use and marine production sectors. The impact of additional factors such as socioeconomic pathways, level of warming, and CO_2 fertilization are also quantified.

The GLOBIOM and MAgPIE models were used to estimate the impact of climate change on EU-28 production (area and yield). For crops cultivated in the EU, climate change impacts on winter wheat, oil seeds and sugar crops are lower than impacts on corn. For example, the EPIC model finds large negative impacts for corn in Southern Europe, but finds cereals such as wheat are more resilient due to their response to CO_2 concentrations. The results vary with climate model and crop model, and whether CO_2 fertilization is included.

The change in relative competitiveness under climate change induces a reallocation of agricultural practices between European countries. Changes in relative profitability result in agricultural losses in Southern and Eastern Europe, but gains in Northern, Western, and Central Europe.

The GLOBIOM model estimates that the economic costs on agriculture for producers is 1.7 billion Euros (RCP4.5 in 2050). Costs for the producers are mostly negative, but vary

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with model and whether CO2 fertilization is included. Impacts on corn production represent up to a third of the agricultural losses.

There are also winners and losers, with the Southern part of Europe experiencing the largest losses, but gains for Northern and Central-Eastern countries, which benefit from a reallocation of agricultural activities. Many of the changes in Europe are driven by change in other competing production sites, world regions and cultivation options.

Forestry and Fisheries

Forestry is a sector with long life-times, and high risk from climate change. As with agriculture, forest growth may be enhanced by some processes but 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.

For forests, the analysis has assessed the change on forest growth and harvest potentials. The biophysical forest model G4M estimates that increased temperature and decreased precipitation could lead to a reduction in the biomass and growth rate of forests in Southern Europe, especially towards 2070 under RCP8.5. Both GLOBIOM and MAgPIE estimate that Northern parts of Europe could benefit from climate change and increase their forestry areas. Under RCP8.5 and without CO_2 fertilization, GLOBIOM estimates the costs of climate change for forest production at 63 million Euros for the producer side and 670 million Euros for the consumer side.

The analysis has also assessed the impact of climate change on forest fires, using the Wildfire Climate Impacts and Adaptation Model (FLAM) along with IIASA's global forestry model G4M. The results estimate that the burned area in Europe could increase significantly in Europe, especially under the RCP8.5 scenario, under which the burned areas could more than double compared to the present-day. The regions with the highest shares of burned areas are found in Portugal, Spain, South of France and Greece.

Climate change will also impact **fisheries**, with changes in abiotic (sea temperature, acidification, etc.) and biotic conditions (primary production, food webs, etc), affecting reproductive success and growth, as well as the distribution of species. Similar risks exist for freshwater fisheries and aquaculture. While fishing activities are the dominant factor affecting fish stocks, climate change will add additional pressure.

The analysis in COACCH indicates that under all scenarios, there is a decline in capture production globally, although there are strong regional differences. Fish stocks are highly mobile and can partly mitigate negative changes: this means that fisheries near the equator are affected more negatively and may migrate to Northern latitudes that

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may gain. The impacts on EU Member States experience depends on the biophysical impact model and the degree of warming.

The results from GLOBIOM estimate all EU countries are projected to experience declines in marine productive capacity from climate change, with the most serious impacts in Denmark, Spain, France and the UK. It estimates a reduction of 3 to 9 million tonnes in annual catches by 2050. However, the MAgPIE model estimates an increase in marine fish catches in North-Western Europe due to climate change. It is noted that both models do not consider additional impacts from marine heat extremes and ocean acidification.

Health

There are a number of health impacts from climate change. These include directimpacts, such as heat-related mortality, deaths and injuries from flooding, etc., but alsoindirect impacts, e.g. from climate change affecting vector-, food- and water-borne disease. There are also risks to the delivery of health services and health infrastructure.

COACCH has assessed the impact of climate change on heat-related mortality (see D2.6, Non-market impacts: health, Ščasný et al., 2020). This has included an analysis of the urban heat island effect. When this is included, the spatial distribution of temperature projections in Europe changes, with rising risks for highly populated cities, even for low warming scenarios.

For Europe (EU28), the estimated total number of excess deaths from heat is estimated at 85,000 (RCP2.6), 145,000 (RCP4.5) and 300,000 (RCP8.5) by the end of the century. Heatwaves account for 40-50% of this total heat- related mortality. These overall estimates are higher than previous estimates, reflecting updated climate projections and also the inclusion of excess heat. The highest number of fatalities are in southern and central Europe.

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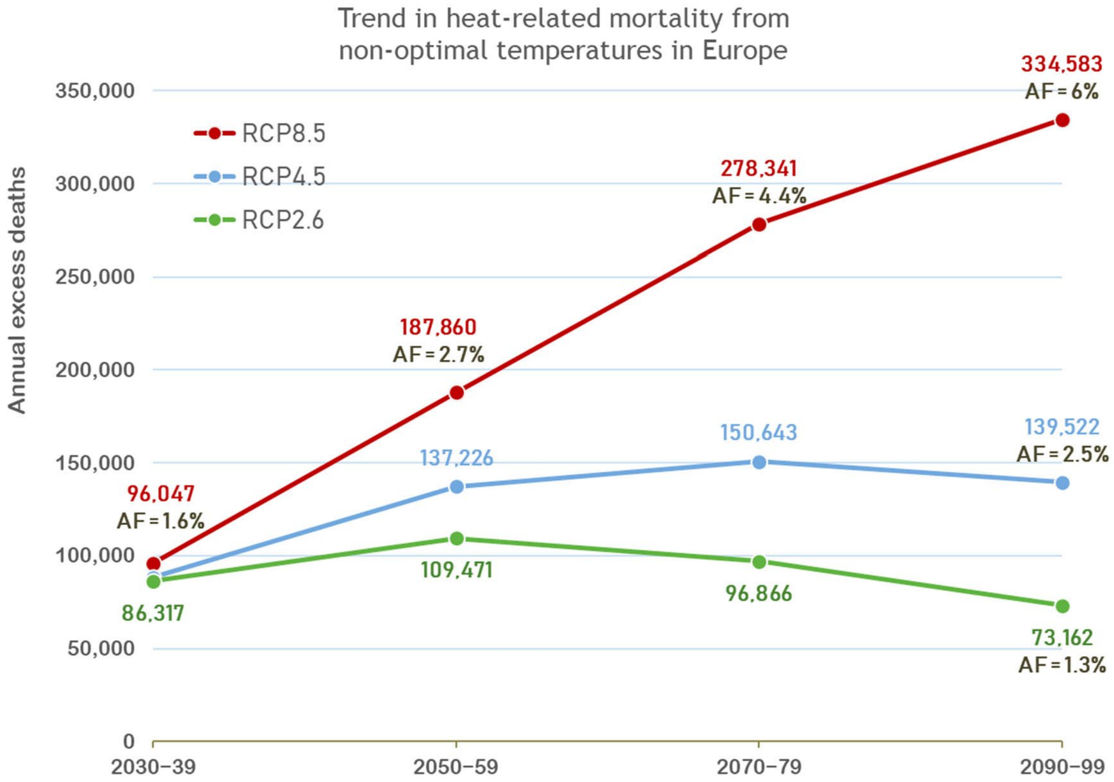

Figure 2.7.7: Trend in annual excess deaths attributable to heat (moderate and excessive) in Europe.

Alongside this analysis, the COACCH project has also derived new estimates for the willingness to pay to reduce the risks of premature mortality, specifically for the heat-related context. This was based on contingent valuation surveys in Spain and the UK. Interesting WTP values were very similar in both countries, and the results were adjusted and transferred to provide average European values. These values have then been applied to the impacts estimated in the figure above.

Two values are shown. The first includes all heat-related mortality, from both moderate and excess heat. The second only includes the mortality associated with heatwaves, as this is the specific context in which the WTP values were derived. This assumes that on average, heat-waves are responsible for approximately 45% of all heat-related fatalities: this proportion was based on a detailed country-specific analysis in the COACCH project.

Table 2.7.8: European Heat -related Health Impacts (Economic Costs) for Various RCP scenarios (no adaptation). Top. All heat-related mortality. Bottom. Heat-wave related fatalities only. No adaptation or acclimatisation, VSL approach.

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All heat	**RCP2.6-SSP2**	**RCP4.5-SSP2**	**RCP8.5-SSP5**
2050s / mid century	€228 Bn/yr	€285 Bn/yr	€390 Bn/yr
2090s /end century	€152 Bn/yr	€290 Bn/yr	€695 Bn/yr

Heat-wave only	**RCP2.6-SSP2**	**RCP4.5-SSP2**	**RCP8.5-SSP5**
2050s / mid century	€102 Bn/yr	€128 Bn/yr	€176 Bn/yr
2080s /end century	€68 Bn/yr	€130 Bn/yr	€313 Bn/yr

Values are presented as additional impacts relative to the baseline period, from the combination of climate and socio-economic change, and are presented as undiscounted values in future years in current prices.

These results indicate that these non-market impacts could be very large, in fact, they are larger than for the other sectors reported in this Deliverable. The results also indicate the large benefits of mitigation policy, i.e. from the more extreme RCP8.5 scenarios, to RCP4.5 and again down to RCP2.6. These show large economic benefits from mitigation from avoided health-related impacts, with very large annual benefits.

However, there are a number of caveats with these estimates (see Chiabai et al.,2018). First the physical impacts calculated do not take account of physiological acclimatisation to heat over time. Accounting for this would reduce down the estimated impacts (numbers). Second, the monetary values derived are based on the full Value of Statistical Life estimates from the WTP study. In practice, the period of life lost for manyheat-wave related deaths may be short. Other studies have accounted for this by adjusting the VSL estimate, for example deriving a Value of a Life Year Lost, and applyingthis. This leads to significantly lower monetary values.

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On the basis of Hajat et al., (2014) we assume that an average of one year of life is lost as a result of heatwave events across Europe. The VOLY can be calculated either directly, by undertaking a survey that elicits such measures (e.g. Desaigues et al. (2011)), or indirectly by calculating the number of years remaining by those expressing a WTP for a VSL value, and dividing the VSL by this number, adjusted by the probability of death in each successive year, and by application of the discount rate. The direct VOLY value used in appraisal has typically been Euro 50,000 whilst the indirect VOLY based on the VSL derived in D2.6 is rounded to Euro 100,000. In this application we use the latter VOLY.

Table 2.7.9: European Heat -related Health Impacts (Economic Costs) for Various RCP scenarios (no adaptation). Top. All heat-related mortality. Bottom. Heat-wave related fatalities only. No adaptation or acclimatisation, VSL approach.

All heat	RCP2.6-SSP2	RCP4.5-SSP2	RCP8.5-SSP5
2050s / mid century	€10.9 Bn/yr	€13.7 Bn/yr	€ 18.8 Bn/yr
2090s /end century	€7.3 Bn/yr	€14.0 Bn/yr	€33.5 Bn/yr

Heat-wave only	RCP2.6-SSP2	RCP4.5-SSP2	RCP8.5-SSP5
2050s / mid century	€4.9 Bn/yr	€6.2 /yr	€8.5 Bn/yr
2080s /end century	€3.3 Bn/yr	€6.3 /yr	€15.1 Bn/yr

Values are presented as additional impacts relative to the baseline period, from the combination of climate and socio-economic change, and are presented as undiscounted values in future years in current prices.

The two tables show very large annual benefits from mitigation, i.e. in reducing high warming scenarios, but the size of the benefit obviously varies with the approach to valuation.

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The COACCH analysis has also considered the potential benefits of adaptation reducing excess heat related fatalities. There is 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; Toloo et al, 2013). There has also been economic analysis of the potential BCRs of such systems, and how these will change with climate change, that takes account of rising benefits (Chiabai et al., 2018), but also the rising resource costs (Hunt et al., 2017) from the schemes being more frequently triggered. Such schemes are very site- and context-specific, but it is possible to derive some indicative estimates by looking at the potential for national systems, operated across Europe under future climate scenarios.

For this analysis the focus has been on national level heat alerts – rather than individual city plans. This has considered the potential benefits of a Heat-Health Watch system (HHWS). This has the merit of being flexible with respect to the degree of climate variability and change that occurs over the lifetime of the system. The analysis is based on resource cost data derived from the England HHWS (Hunt et al., 2016) and then transferred to the European context. In this system, heat-wave weather warnings are issued, with associated health care professional response, with four levels of action (awareness, alert, heat-wave, emergency), with progressively rising intervention.

The benefits of implementing a heat warning system is the reduction in health impacts. The benefits are determined by the effectiveness of the warning system. To date, there is no published quantitative evidence of the effectiveness of these systems across the EU. However, two studies in Europe include Fouillet et al (2008) that compares deaths before and after HWS implementation in France, in 2003 and 2006, respectively and Morabito et al (2012) that undertake the same comparison in Florence, Italy. Whilst the French study finds effectiveness of 68% when the number of fatalities avoided are used as the measure of effectiveness, the Florentine study finds effectiveness of 9%, using the same metric. In the absence of any other data we adopt the assumption that for thecore analysis, the rate of effectiveness is the mid-point between the two observations from the European studies. The mid-point is 38% and, given the lack of evidence on which to differentiate, we apply this same value across Europe.

The benefit-cost ratios for implementing HHWS across European regions have been estimated, using the VSL and VOLY metrics, respectively. When the VSL metric is applied, the benefit-cost ratio is greater than 1 in all European regions, under all future scenarios. If the VOLY metric is applied, the result is the same apart from the fact that the ratio is below 1 in Southern Europe. This reflects the fact that the resource costs increase faster than benefits in this region (i.e. managing heat-related health effects are likely to place a major strain on health care systems). This highlights that in these areas, heat alert systems are likely to be insufficient – and public authorities may need to look at broader portfolios of complementary adaptation options.

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Table 2.7.10: Benefit-Cost ratios for Health Heat Adaptation: European Regions mid-century– Top VSL Mortality values. Bottom VOLY values.

VSL		**Period 2050-59**
Northern Europe	**RCP 2.6**	**32.9**
	RCP 4.5	**32.9**
	RCP 8.5	**27.7**
Central Europe	**RCP 2.6**	**5.1**
	RCP 4.5	**4.8**
	RCP 8.5	**5.5**
Southern Europe	**RCP 2.6**	**1.3**
	RCP 4.5	**1.4**
	RCP 8.5	**1.5**
VOLY		
Northern Europe	**RCP 2.6**	**15.8**
	RCP 4.5	**15.8**
	RCP 8.5	**13.3**
Central Europe	**RCP 2.6**	**2.5**

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	RCP 4.5	**2.3**
	RCP 8.5	**2.6**
Southern Europe	**RCP 2.6**	**0.6**
	RCP 4.5	**0.7**
	RCP 8.5	**0.7**

Biodiversity and Ecosystem Services

COACCH has not developed new modelling and analysis for biodiversity and ecosystem service impact assessment and valuation. However, a European policy analysis has been developed by extending the policy case study presented earlier in this report. This uses the analysis undertaken for the UK Climate Change Committee on the UK Climate Change Risk Assessment, and transfer this to consider the equivalent issues at the European scale.

For each of the risks analysed in the UK CCRA, described in the preceding section, we present information on the effectiveness and barriers to implementation of the adaptation measures, as well as an overview of data relating to the costs and benefits of such measures.

In this part of the analysis, we then provide an indicative rating on their transferability of the analysis from the national to the European scale. The rating is disaggregated across three dimensions: significance of climate change risk at EU scale; likely effectiveness of identified adaptation options, and; likelihood of benefit: cost ratio > 1, based on the authors' judgement.

Table 2.7.9: UK to EU Adaptation transferability

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Risk / Opportunity	Significant climate change risk at EU scale	Likely effectiveness of identified adaptation	Likelihood of benefit: cost ratio > 1
NE1. Risks to terrestrial species and habitats from changing climatic conditions and extreme events,	🟩	🟧	🟧
NE2. Risks to terrestrial species and habitats from pests, pathogens and invasive species	🟩	🟩	🟩
NE3. Opportunities from new species colonisations in terrestrial habitats	🟩	🟧	🟧
NE4. Risk to soils from changing climatic conditions, including seasonal aridity and wetness.	🟩	🟧	🟧
NE5. Risks to natural carbon stores and sequestration	🟩	🟧	🟧
NE6. Risks to and opportunities for agriculture and forests	🟩	🟧	🟩
NE7. Risks to agriculture from pests, pathogens and invasive species	🟩	🟩	🟩
NE8. Risks to forestry from pests, pathogens and invasive species	🟩	🟩	🟩
NE9. Opportunities for agricultural and forestry productivity from new/alternative species	🟩	🟧	🟧
N10. Risks to aquifers and agricultural land from sea level rise, saltwater intrusion	🟩	🟩	🟩

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N11.Risks to freshwater species and habitats from changing climatic conditions and extreme events	🟩	🟧	🟧
N12. Risks to freshwater species and habitats from pests, pathogens and invasive species	🟩	🟩	🟩
N13. Opportunities to freshwater species and habitats from new species colonisations	🟧	🟧	🟧
NE14. Risks to marine species, habitats and fisheries from changing climatic conditions	🟩	🟩	🟩
NE15. Opportunities to marine species, habitats and fisheries from changing climatic conditions	🟧	🟧	🟧
NE16. Risks to marine species and habitats from pests, pathogens and invasive species	🟩	🟧	🟧
NE17. Risks and opportunities to coastal species and habitats due to coastal flooding, erosion and climate factors	🟩	🟩	🟩
NE18. Risks and opportunities from climate change to landscape character	🟩	🟩	🟩

Key

High	🟩
Medium	🟧
Low	🟥

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This provides an initial indication – based on our judgement – as to whether the findings derived from this national evidence base could be applied at the scale of EU Biodiversity policy. As shown in the table above, it is clear from our assessment that the risks and opportunities identified in the UK are relevant to EU adaptation policy. Furthermore, based on our indicative rating score, we judge that the economic evidence compiled in relation to adaptation responses to these risks has either medium or high transferability to the EU context. However, this evidence base is notably thin and incomplete; future research should look to strengthen this and so better support the development of a robust adaptation strategy for the sector.

3. Discussion and conclusions

3.1 Policy effectiveness in agricultural business (Lead: PIK)

Our scenario analysis compared different policy paradigms for European climate policy. They result in different outcomes for business opportunities, consumers and environment, and show a large heterogeneity in the possible strategies to mitigate GHG emissions.

- Within the land use sector, emissions can be mitigated by consumers (via changed dietary patterns and reduced food waste) and by producers (via more efficient fertilization practices or reduced land expansion). In linkage with the energy sector, emissions can be mitigated by the cultivation of bioenergy, offsetting fossil fuel emissions in the energy sector but increasing some emissions in the agricultural sector due to required fertilization and additional land-expenditure. Bioenergy cultivation becomes only attractive for climate change mitigation if combined with Carbon Capture and Storage, which in turn however raises sustainability concerns. Finally, emissions can also be transferred to other world regions by imports or exports; whether the global net-effect is positive or negative depends on the relative emission-intensities of the trading world regions. We observe major changes in trade patterns between policy scenarios only in the case of dietary shifts; interestingly imports of oilcakes are reduced while exports of crops and livestock remain rather unaffected.
- For producers, policies without dietary change and with high bioenergy usage may be more attractive due to the higher overall value of production. It has to be cautioned that this additional value is also the consequence of inefficiencies, food waste and unhealthy dietary patterns. The increased

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value of production therefore does not necessarily result in an improved societal outcome. Likewise, the reduction of production quantities could also be considered a chance for improving quality of production or as a chance of improving profits via a reduction of production costs. In our scenarios, we for example observe that in scenarios of strongly reduced demand, croplands are expanded and production is extensified. Evaluating the options for extensification to save costs, as well as to improve quality (and willingness to pay) of consumers should be addressed by future research.

- For consumers, we observe very different outcomes depending on whether mitigation is achieved through demand-side measures or supply side measures. Demand-side measures that lead to more healthy dietary patterns also strongly reduce food expenditure despite the simultaneous increase in the consumption of fruits and vegetables as well as staple crops; the results however need to be placed in the context that the expenditure shares only include the value of the agricultural commodities. Final consumer expenditures are considerably higher as the value-added of marketing and processing by far exceeds the value of agricultural products in Europe. The drastic reductions of expenditure for agricultural products will therefore likely only results in a minor reduction of final food expenditure of consumers.
- For the environment, all analysed scenarios were by definition in line with a 1.5° climate target. However, the relative contribution of agriculture compared to other sectors differed. Market and policy-steered scenarios had a lower contribution from agriculture, while the dietary change scenarios had a higher mitigation contribution. However, the mixed and the market scenario also provided high quantities of bioenergy which contributes to emission mitigation in the energy sector. Nitrogen surpluses were lowest for the scenarios of behavioural (diet) change and the current paradigm, while they increased more in the market and policy-steered scenarios due to their low improvement in NUE. In terms of land-use change in Europe, the scenarios with diet changes showed a substantial reduction in pasture areas, but at the same time increasing cropland areas. This latter increase was not used to increase exports, but to extensify production. No substantial international leakage effects due to European policies were observed in the scenarios, most likely as the other world regions also had climate targets in place in all scenarios. From a global environmental perspective, the differences in terms of environmental impacts of the analysed policies were most pronounced for nitrogen pollution, as Europe is here an international hotspot. In contrast, landuse changes in Europe are small when compared to international landuse changes.
- Future research should put more attention to differentiating measures (such as changed dietary patterns or improved nitrogen use efficiencies) from the policies that incentivize, enforce, nudge or persuade actors to adopt these

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measures (Gaupp et al, in preparation). This would also largely improve the evaluation of the distributional consequences such policies may have.

- A further interesting variant of our scenario analysis for future research would be to analyze the effect of our European policy strategies under a setting where all other world regions do not engage in GHG mitigation; in contrast to the scenarios analysed here, the carbon leakage and the interaction with other world regions would be considerably stronger than in the analysed case, where GHG policies in other world regions effectively prevent the relocation of production to other world regions.

○ 3.2 Policy effectiveness in industry and business (Lead: UNIGRAZ)

Physical climate risks and adaptation in the industrial sector

- For the manufacturing industry, the most prevalent climate hazards are storm, heat, drought and water shortage, and coastal and riverine flooding.
- The most frequent physical climate risks arise in the form of damages to production stock and material, reductions in economic performance and higher costs, and damages to production and logistics facilities.
- Physical climate risks to the manufacturing industry can be reduced by a number of measures that can be taken at the company level: risk management, capacity building, and information and R&D. So far, ecosystem-based adaptation is only implemented in a few cases e.g. to increase water efficiency.
- While most of the considered adaptation options are pro-active, incremental adaptation dominates; the risk of temporal or permanent business disruption is mentioned, but not linked to transformational adaptation.
- Public adaptation measures, such as policies supporting or mandating adaptation, and warning and observation systems, can enable and support private adaptation action.
- More research is needed on the feasibility and effectiveness of adaptation actions for specific subsectors (e.g. the chemical industry), risks and regions.

Consequences of supply chain interruptions for European industries and implications for adaptation

- From climate change and urbanization, extreme weather events are increasingly exceeding the design thresholds of current production facilities.
- Globalization of production networks means that extreme weather events can have impacts far from where they directly hit via supply chain networks.
- We find that supply chain shocks from upstream input suppliers significantly reduce downstream trading partners' export performance.
- However, having a diversified input supplier network dampens the shock as it enables firms to more easily find substitutes for damaged suppliers. A diversified

supply chain may come at a trade-off with supply chain efficiency in normal times.

- Due to their geographical centrality and their role in global production networks, countries in Southeast Asia and countries situated in Europe tend to have less concentrated input supply chains compared to countries in Africa, South America and North America.
- Within Europe, industries and countries strongly differ in the level of supply chain diversification. We find that agriculture, fishing, mining and quarrying and electricity, gas and water are the industries with the least diversified supply chain, and consequently most exposure to shock propagation due to large switching costs. Romania, Bulgaria and Italy are the countries with the most highly concentrated input supply chains.
- The size of the relevant substitute suppliers plays a role in the mediating effect of input supplier: in case of a supply chain shock, it is far more important to have multiple large input suppliers that can substitute for missing input, than many suppliers of all sizes.
- Firms may use this information to make decisions surrounding the amount of efficiency in normal times they are willing to forfeit for supply chain robustness in case of disaster.
- Governments and other aid organizations may use this information in designing policies and investments that promote supply chain diversity as well as planning for extreme weather shocks that propagate along the supply chain.

An assessment of adaptation pathways for European seaports and supply chain networks

- The assessment of adaptation pathways for supply chain networks in the North Sea Region provides some insight for the future of relevant European and national policies. Climate adaptation is becoming increasingly important in this field, with the importance of resilient supply chains becoming all the more apparent, particularly in light of the COVID-19 pandemic and its repercussions for global trade.
- The results of this initial, high-level assessment of adaptation in supply chain networks, demonstrates the value of green measures, particularly as an early no-regret approach with strong co-benefits.
- We note additionally that the highest ranked pathways all incorporate supply chain management measures either in the medium or long term. These measures are not only effective at reducing climate change damages, but are also easy to implement and maintain.
- Finally, we note that digitalisation measures feature in two of the well performing pathways. These measures, while offering less damage reduction than alternatives, are relatively low cost, and offer important flexibility across scenarios. They can therefore complement supply chain management measures in the medium and long term.

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- European policies such as the EU Adaptation Strategy and the Trans-European Transport Network (TEN-T) will be vital in advancing these adaptation strategies. The TEN-T Core Network is to be completed by 2030, and implications for ports, transport networks, and the broader supply chain should be taken up in the planning process.
- Green measures, as well as risk management measures are low cost actions that can be implemented in the short term while leaving next steps open for adjustment. Furthermore, supply chain management measures, digitalisation, as well as more general improvements to the transport network should also be at the forefront of ongoing adaptation efforts.
- Adaptation priorities can also be streamlined through funding and investment mechanisms. Significant transport projects in the EU are funded through the Connected Europe Facility (CEF), the European Regional Development Fund (ERDF), and the Cohesion Fund (CF) (Climate-ADAPT). The new EU Adaptation Strategy highlights the importance of following its climate resilient guidelines for new infrastructure projects.
- The EU's post-COVID recovery plan (EC, 2021b) set out 750 billion Euros, the bulk of which (721 billion Euros) is earmarked for "Cohesion, resilience and values" and will go to the ERDF and CF. Incorporating adaptation measures and pathways into these funding streams can ensure that future transport and supply chain developments are robust and resilient to a range of future climate scenarios.

○ 3.3 Policy effectiveness in insurance (Lead: IIASA)

- Flood risk in the EU is expected to increase with both climate and socioeconomic change. Insurance is an effective mechanism to limit financial vulnerability to this risk of both citizens and governments.
- The design of insurance systems varies significantly across EU countries, with some systems being better able to cope with issues such as unaffordability of premiums, low insurance uptake, and moral hazard.
- These issues affect households at risk of flooding, the insurance providers as well as the public household, who often provides financial aid when insurance coverage is insufficient.
- This study addresses the policy effectiveness of various flood insurance policies in EU countries and the UK on a macroeconomic scale. For that purpose, we apply riverine flood risk data up to 2050 that was calculated using a state-of-the-art flood risk simulator, estimate flood insurance premiums and household responses to flood risk and insurance incentives using a partial equilibrium model, and apply these parameters in a Computable General Equilibrium (CGE) model.
- We find that flood damages in 2050 lead to lower GDP as well as lower private and public welfare in all EU regions with particularly strong effects in South-Eastern and Southern EU as well as Romania and Poland. However, we also find that some insurance systems are better able to cope than others with issues

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posed by high or rapidly rising flood risk, particularly when considering private and public welfare measured as the consumption possibilities of each household.

- While the majority of EU regions currently maintain a private insurance system where uptake of coverage is optional and premiums are risk-reflective, the adverse macroeconomic impact of flood risk appears to be smaller when flood insurance is to some extent public, insurance purchase requirements are maintained, and risk-based pricing is limited. While no engagement in the insurance activities may seem as the cheapest option at the first sight for policy-makers, installing an adequate flood insurance mechanism will limit additional expenditures arising from households being insufficiently insured against damages.

- The Italian case study of residential insurance against natural hazard, offers a particularly interesting example of "adaptation" mis incentive or "maladaptation". The system of state *compensations* of disaster losses, which does not constitute a *duty-to-compensate,* but connotes a long-establish customary practice, impedes private insurance markets.
- The *tripartite* mandatory nature of the last insurance scheme that obliges property owners to underwrite insurance contracts, insurers to become part of the pool, and credit institutions to buy cat-bonds, does not abide with the rules of free internal market and disincentivize individual risk-sensitive behaviour. It embraces entirely solidarity and disowns individual or collective responsibility for risk. The abridged risk premiums determined according to sole typology of the buildings and the chosen level of protection does not encourage individual risk reduction. Finally, the proposed scheme cares little about the changing magnitude of risk from extreme weather and climate-related events, driven by societal and environmental changes.
- A smooth transition towards a reasonable risk pricing over a period of say thirty years or longer may send a signal to real estate market that delivers tangible outcomes gradually.
- The risk and financial burden should be equally split among public and private entities engaged voluntarily in a partnership. The partnership itself should be based on sound risk assessment and every house owner or lessee should find it easy to access the information about the risk exposure of the owned or leased property.
- The scheme should differentiate between levels of hazard exposure and, to the extent possible, pool the risk among the property owners within the same or similar categories of risk.
- Any duplicity between existing financial and economic instruments, including payments for water services or indivisible municipal services (the costs of which is recovered by property taxes or charges) and the envisaged scheme should be avoided. In the case of flood risk this may result in risk premium discounts proportionally to the amount of tax or service charges already paid.

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○ 3.4 Policy effectiveness in infrastructure, built environment, and transport for investments (Lead: GCF)

Coastal Flooding

- Additional adaptation measures combined with coastal protection (elevating of infrastructure, flood-proofing of infrastructure, coastal retreat) reduce total cost of sea-level rise in any case.
- On EU27-level coastal retreat from unprotected areas is most efficient in terms of reducing total cost of sea-level rise - followed by flood proofing of infrastructure and infrastructure elevation.
- On country-level the effectiveness of additional adaptation measures might be different, depending on the coastal capital stock of the country.

River Flooding

- Adaptation standards include baseline flood protection height (BaseHeightStd), baseline flood probability standard (BaseProbStd) and optimal flood protection standard (OptimalStd).
- Europe is expected to experience between €27 billion under optimal and €67 billion euros under the baseline flood protection standard assumptions.
- The results are more sensitive to flood adaptation assumptions than the climate realization.

Policy effectiveness of urban coastal adaptation strategies to avoid socio-economic tipping points in cities under high-end sea level rise

- The case study showed that the storyline of the stakeholders, namely that a tipping point may occur in a coastal city due to concerns about the flood risk, is plausible under some conditions. We simulated the socio-economic tipping point of a sudden drop in house prices for a stylized case with characteristics of Rotterdam. This city is archetypical for coastal cities with an engineered coastal defense, and currently has very high protection, against a 1:10,000 year flood event. We examined if sudden drops in house prices may occur before 2200, under four flood risk policies.
- We found that even in a city with such high initial protection, and with a strategy that dynamically adapts to the changing conditions, house price collapses may occur. If the climate tipping point of accelerating sea level rise occurs, the likelihood of the house price collapse is large, and can only be avoided with a very proactive management strategy and with a smooth policy making process that enables short implementation times. If the policy is not proactive, or the implementation time of measures becomes too long, socio-economic tipping points will likely happen.
- Under IPCC likely range scenarios (which do not reflect the climate tipping point of accelerating sea level rise), house price collapses may still occur. But, these

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only occur when assuming a housing market where flood risk perceptions, and not the rational flood risk, dominates the price dynamics. This has an important policy implication. Managing the flood risk is one thing, but informing the general public about the risk is another. If the government can manage these perceptions of risk especially in the aftermath of a flood or near miss event, panic may not overtake the housing market and tipping points may be avoided.

- With a very proactive flood risk management strategy, house price tipping points can be completely avoided under the IPCC likely range scenarios. The proactive flood risk management strategy may also avoid tipping points if the climate tipping point of a strongly accelerating sea level rise happens. In this case, it is very important that the measure implementation time is so fast that it can keep up with the high rate of sea level rise.
- In order to give a sound interpretation of these findings, we need to point at two limitations of the highly stylized case study. The first limitation is the limited set of policy actions, which does not completely cover all possible interventions a government or residents can do. For example, in many scenarios the real estate on the unembanked residential area gradually deteriorates into a situation in which the properties flood every year, and their value is practically zero. However, depending on the institutional context, it is more likely that residents who can afford it will sell or abandon their properties and relocate to safer grounds. In other contexts, the government will intervene in the area, for example by forcing retreat, constructing embankments, or by redesigning the area to accommodate for the higher water levels.
- The second limitation is the highly stylized representation of the housing market, which has only captured the possible impact of expected property damage to the housing prices. In reality, there are many factors with an influence on the housing price. On the demand side, some factors are: the number of people wanting to live in a particular neighbourhood, the affordability of the houses, speculative demand, interest rates and the availability of mortgages. On the supply side, some factors are: the number of people wanting to sell their house, and the number of new houses that are constructed. The housing market is notoriously volatile due to complex interplays of all these (and other) factors. To date, there is only limited evidence that flood risk plays an important role on house prices (Beltran et al., 2018; Bin and Landry, 2013). One explanation is that the downside (flood risk) that comes with living close to water is often counteracted by the many upsides of living close to water, such as attractive nature and scenery, and being located close to economic activity which is centred around water. Empirical studies find a small (Beltran et al., 2018) or negligible (Bin and Landry, 2013) persistent price effect of flood risk to house prices. However, both studies also find a strong temporarily price effect in the years after a near-miss event, which decays after some 5-10 years. This price effect we have imitated in the ‘boundedly rational’ housing market.

Adaptation of road infrastructure to river floods

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- In general, to keep flood risk within acceptable range, the current protection levels need to be maintained on the current safety levels. A recent study by Dottori et al. (2021, under review) assessed four adaptation options: raising embankments, constructing retention areas, flood proofing and relocation. This study also showed that such adaptation is generally cost effective. The cost-benefit ratio of construction of retention areas is about 4, the ratio for raising dikes is 2.9, for flood proofing the ratio is still above 1 in large parts of Europe, relocation is only cost-effective in small parts of Europe.
- The COACCH research shows that if the flood protection levels remain on the same level due to the above general river flood risk measures, there is no urgent need to carry out additional flood risk adaptation measures. Nevertheless, each member state has weaker spots in its road network, and adaptation should therefore focus on improving these spots. Especially when budgets are limited, investments can focus on the road segments that are both vulnerable and critical for the overall network performance. Disruptions of such sections cause disproportionally large damage, which may be avoided with tailored interventions. With the development of the new object-based approach, we have provided national road operators and strategic pan-European planners with a tool that works on the continental scale, yet provides a perspective of action on the level of individual road segments. This fulfils a demand of road operators, who want to see results presented on the road segment level as to provide them with a perspective of action.
- New research on flood damage to roads may focus on the role of flow velocity and subsoil conditions on the damage that can be expected to roads after a flood event. Moreover, there is an urgent need for the collection of validation data, because the absence of this data currently hampers the validation and verification of the models. Consistent reporting of experiences with floods therefore is a research priority. Such research could possibly be done with the ‘codesign’ setup used in the COACCH project, and may include both researchers, road operators and other practitioners from the transport sector. Another suggestion is to investigate emergency response costs during flood events, because research in the United States suggests (Vennapussa et al., 2013) that these costs may equal the amount of infrastructural damage, which has been the focus of COACCH. Also, more research needs to be done on the damage to special structures such as bridges and tunnels.
- One interesting question for new research could be if extreme sea level rise and precipitation projections are a reason to counter the current trend of building roads increasingly underground and in tunnels. This is mainly done to avoid nuisance from noise, to improve air quality and because of competition with other sectors for the same land. However, such design choice makes the road networks less robust against floods, and for example may hamper evacuation in case of an extreme event.
- Besides the impacts to the road network, the comparison with PESETA-IV revealed that there are important discrepancies in the existing literature as to

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how large the expected damage to rail infrastructure is. Mulholland et al. (2021, under review) find that the flood damage to rail outnumbers the damage to roads. Further research needs to be done to examine if rail infrastructure is indeed so vulnerable.

- Since we found that the road network is typically rather resilient, and that point-locations such as production facilities are the weakest links in the supply chain, one interesting direction for research could be the terminals where freight is shipped from one mode of transport (e.g. inland waterway transport) to another (e.g. rail or road). These terminals are typically located close to the river, i.e. in the hazard zone, and we suspect that their capacity might be more constrained than the capacity of the road network itself.

○ 3.5 Policy effectiveness in non-market impacts: ecosystems and health for policy makers and research (Lead: PWA)

- This sub-task has undertaken a case study that was co-developed with UK policy makers as part of the deep engagement activities. It has focused on the policy area of national risk assessment and national adaptation programming. The case study has reviewed the evidence, and undertaken additional indicative analysis, to estimate the economic costs of climate change on non-market sectors in the UK for low and high warming pathways, and thus the benefits of mitigation. It has also undertaken a review of adaptation costs and benefits to respond to these risks. The analysis has considered 25 non-market risks, covering biodiversity and ecosystem services, as well as health and well-being. This case study has fed directly into the UK's published 3rd Climate Change Risk Assessment (CCRA3) (UoE, 2021).
- A first finding of the case study is that a significant number of climate threats to non-market sectors have very high aggregate economic costs, estimated at £billions/year in the UK, even by the mid-century. A second key finding is that there is a clear step change in the economic costs of climate change in the UK for these non-market sectors under a 4°C versus a 2°C future. Global mitigation will therefore have very large economic benefits in reducing the impacts to non-market sectors in the UK. The analysis did reveal that there is still less economic evidence on the economic costs of climate change on the natural environment theme than other sectors, although this is driven primarily 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).
- The case study has also provided some key insights, particularly for future research. A key observation is that the risks that national adaptation policy makers work with are very different to the modelled output of projects, even for

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policy focused projects such as COACCH. For example, the list of natural environment risks in the UK's national risk assessment was very large (18 risk categories). Most of these are not covered in current models, for example, the risks of climate change on pests and diseases. Similarly, for health, key risks extend beyond the current focus on heat-related mortality, and include vector, water and food borne disease, as well as impacts on health services and health infrastructure. This indicates further work is needed to match modelling outputs to policy needs.

- With respect to adaptation, the evidence review found an increased body of evidence, and identified potentially high economic benefits from further adaptation for most of the risks to non-market sectors (natural environment and health). The analysis found that many early adaptation investments in non-market sectors deliver high value for money, with positive benefit to cost ratios. At the same time, some decisions and actions can be delayed: a key priority 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 is still relatively little application of the economics of adaptive management for non-market sectors. There is also a need to improve the economic analysis of real-world adaptation for non-market sectors, particularly for non-technical options. Both of these areas are therefore identified as research priorities.

○ 3.6 Policy effectiveness for policy makers (Lead: PWA)

- The final sub-task of this deliverable extends the analysis for each of the sectors in WP2, and brings together and assesses the potential benefits of mitigation and adaptation policy at the EU level.
- For each sector, the potential economic costs of climate change (the costs of inaction) are assessed for future RCPs scenarios. This shows very large damage costs are projected for direct damages (e.g. coastal and river sector), but also for non-market sectors notably health. This is important as these non-market sectors are not captured in the COACCH macro-economic analysis (as they are not included in the CGE modelling).
- The results also show the large benefits of mitigation, as shown by the comparison of different RCP scenarios. The annual benefits of mitigation to the EU are very large, however, these benefits mostly arise after 2050, and are most important in reducing down the impacts of high warming scenarios.
- A key finding from this analysis is that even if the Paris Goals are achieved, the Economic Costs of Climate Change in the EU will be still large – and furthermore - impacts over the next 25 years can only be reduced significantly with adaptation.
- This task has therefore also looked at the economic benefits of adaptation in Europe, estimating the reduction in impacts, and for several sectors, it has also looked at the costs of adaptation. The first finding is that adaptation can significantly reduce the economic costs of climate change and it is very

effective in reducing down impacts over the next twenty years, as well as later periods. The second finding is that adaptation looks to have high benefit to cost ratios: early adaptation therefore makes good economic sense, and can act complementarily to mitigation.

- This information provides key inputs of relevance for European policy makers, and has fed into a separate policy brief. The results show that mitigation and adaptation both have important benefits, and that a complementary mix of both are needed.

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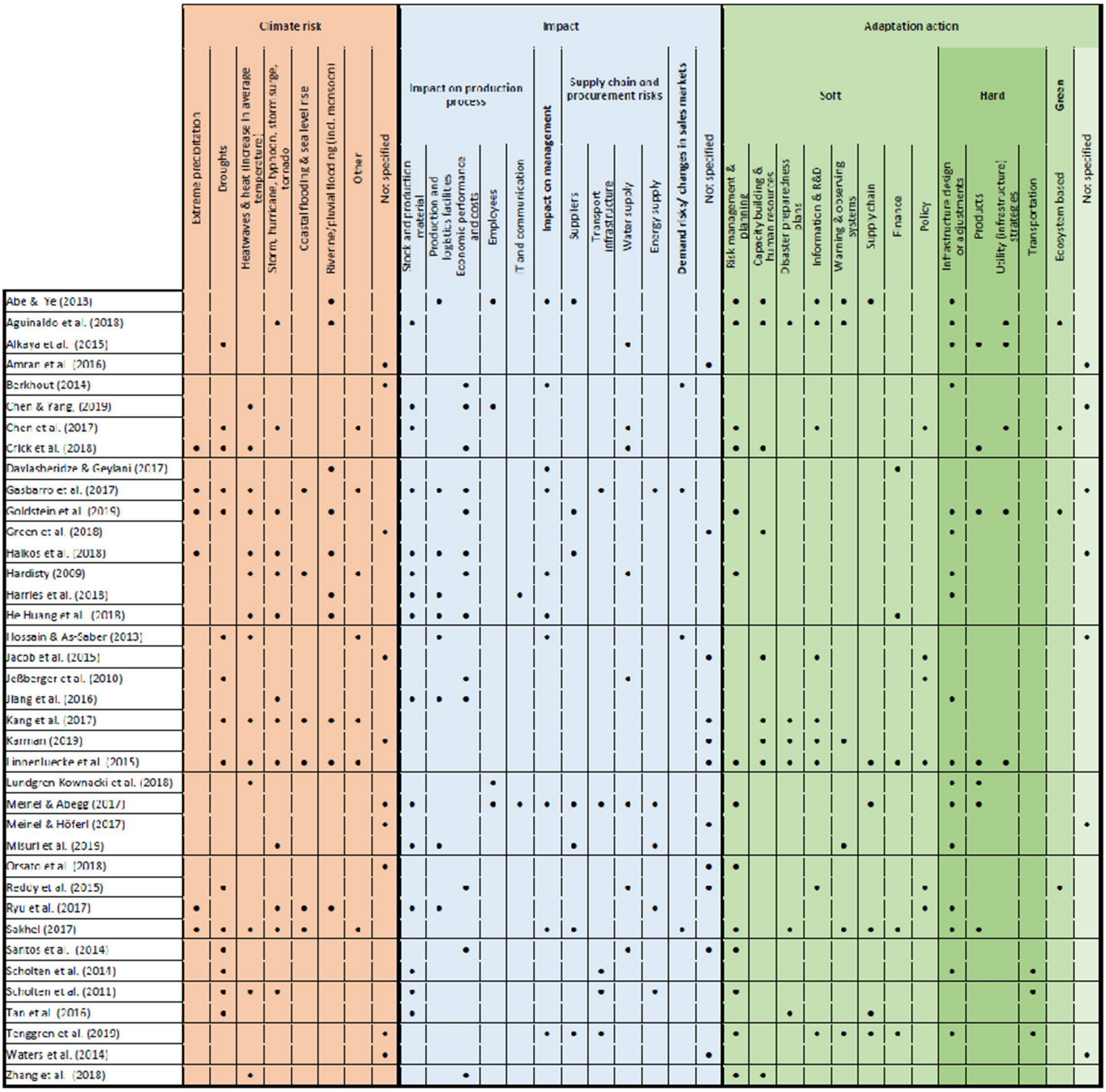
Appendix

Table A1: Studies on physical risks, impacts on industry and adaptation actions



	Climate risk								Impact												Adaptation action													
									Impact on production process						Supply chain and procurement risks						Soft								Hard				Green	
	Extreme precipitation	Droughts	Heatwaves & heat (increase in average temperature)	Storm, hurricane, typhoon, storm surge, tornado	Coastal flooding & sea level rise	Riverine/pluvial flooding (incl. monsoon)	Other	Not specified	Stock and production material	Production and logistics facilities	Economic performance and costs	Employees	IT and communication	Impact on management	Suppliers	Transport infrastructure	Water supply	Energy supply	Demand risks/ changes in sales markets	Not specified	Risk management & planning	Capacity building & human resources	Disaster preparedness plans	Information & R&D	Warning & observing systems	Supply chain	Finance	Policy	Infrastructure design or adjustments	Products	Utility (infrastructure) strategies	Transportation	Ecosystem based	Not specified
Abe & Ye (2013)						●				●		●		●	●						●	●		●	●	●			●					
Aguinaldo et al. (2018)				●		●			●												●	●	●	●	●				●		●		●	
Alkaya et al. (2015)		●															●												●	●	●			
Amran et al. (2016)								●												●														●
Berkhout (2014)								●			●			●					●										●					
Chen & Yang, (2019)			●						●		●	●																						●
Chen et al. (2017)		●		●			●		●								●				●			●				●			●		●	
Crick et al. (2018)	●	●	●								●						●				●	●								●				
Davlasheridze & Geylani (2017)						●								●													●							
Gasbarro et al. (2017)	●	●	●		●		●		●	●	●			●		●		●	●															●
Goldstein et al. (2019)	●	●	●	●		●					●				●						●								●	●	●		●	
Green et al. (2018)								●												●		●							●					
Halkos et al. (2018)	●		●	●		●			●	●	●				●																			●
Hardisty (2009)			●	●	●		●		●		●			●			●				●								●					
Harries et al. (2018)						●			●	●			●																●					
He Huang et al. (2018)			●	●		●			●	●	●			●													●							
Hossain & As-Saber (2013)		●	●				●			●				●					●															●
Jacob et al. (2015)								●												●		●		●				●						
Jeßberger et al. (2010)		●									●						●											●						
Jiang et al. (2016)				●					●	●	●																		●					
Kang et al. (2017)		●	●	●	●	●	●													●		●	●	●										
Karman (2019)								●												●		●	●	●	●									
Linnenluecke et al. (2015)		●	●	●	●	●	●													●	●	●	●	●		●	●	●	●	●	●			
Lundgren Kownacki et al. (2018)			●									●																	●	●				
Meinel & Abegg (2017)								●	●			●	●	●	●	●	●	●			●					●			●	●				
Meinel & Höferl (2017)								●												●														●
Misuri et al. (2019)				●					●	●					●			●							●				●					
Orsato et al. (2018)								●												●	●													
Reddy et al. (2015)		●									●						●			●				●				●					●	
Ryu et al. (2017)	●			●	●	●			●	●								●										●	●					
Sakhel (2017)	●	●	●	●	●		●							●	●				●		●		●		●	●	●		●	●				
Santos et al. (2014)		●									●						●			●	●													
Scholten et al. (2014)		●							●							●													●			●		
Scholten et al. (2011)		●	●	●					●							●		●			●											●		
Tan et al. (2016)		●							●														●			●								
Tenggren et al. (2019)								●						●	●	●					●			●	●	●	●		●			●		
Waters et al. (2014)								●												●														●
Zhang et al. (2018)			●								●										●	●												

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