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COACCH

CO-designing the Assessment of Climate CHange costs

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Disclaimer

Dissemination Level		
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CO	Confidential, only for members of the consortium (including the Commission Services)	
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Version log

Version	Date	Released by	Nature of Change
1.1	27/September/ 2021	PWA	First Draft
1.2	28/September/ 2021	PWA	Second Draft following co-ordinator review

Summary

The COACCH Project has produced a series of policy briefs that summarize the project results, as the project has progressed, and at the end. These have been used to provide targeted results for key stakeholders, as well as for wider communication and dissemination of the project. Originally, WP5 anticipated the production of separate deliverables in the form of briefs for the business, the finance, the policy making and the research communities. However, the business, the finance and the policy making policy communities turned to be very similar in their requests of non-technical language and transparency of results. Accordingly, WP5 deliverables and briefs reporting COACCH results have been organized per thematic areas rather than per community types. This has allowed policy briefs to accompany the phases of the project, presenting results as they emerge for communication to stakeholders.

This deliverable compiles the first two policy briefs produced by the project. The first COACCH policy brief was produced near the start of the project. This synthesized the current information on the economic costs of climate change in Europe and identified areas of possible research to explore with stakeholders at the first COACCH workshop. This COACCH policy brief was also prepared to present a state-of-the-art review to inform early European Commission (EC) discussions on forthcoming climate policy. The first COACCH policy brief was cited by EC in the work supporting the EC 2050 long-term strategy ((COM (2018) 773)) and it was used by the EC in the Evaluation of the Adaptation Strategy, (COM/2018/738 final) and cited in the supporting Staff Working Paper for the evaluation.

The second policy brief was produced at the mid-point of the project, and summarized the key results on sectoral impacts of climate change achieved. This was again used to communicate results to COACCH stakeholders, including for policy, research, business and investment stakeholders. The estimates in the second COACCH policy brief were shared with the EC and were cited in the EC Adaptation Mission papers.

The research community is targeted with both the scientific deliverables of the project and with the open databases from COACCH which are disseminated through the COACCH scenario explorer (COACCH Deliverable 5.2) and the COACCH extended climate change impacts and policy database (COACCH Deliverable 5.1).

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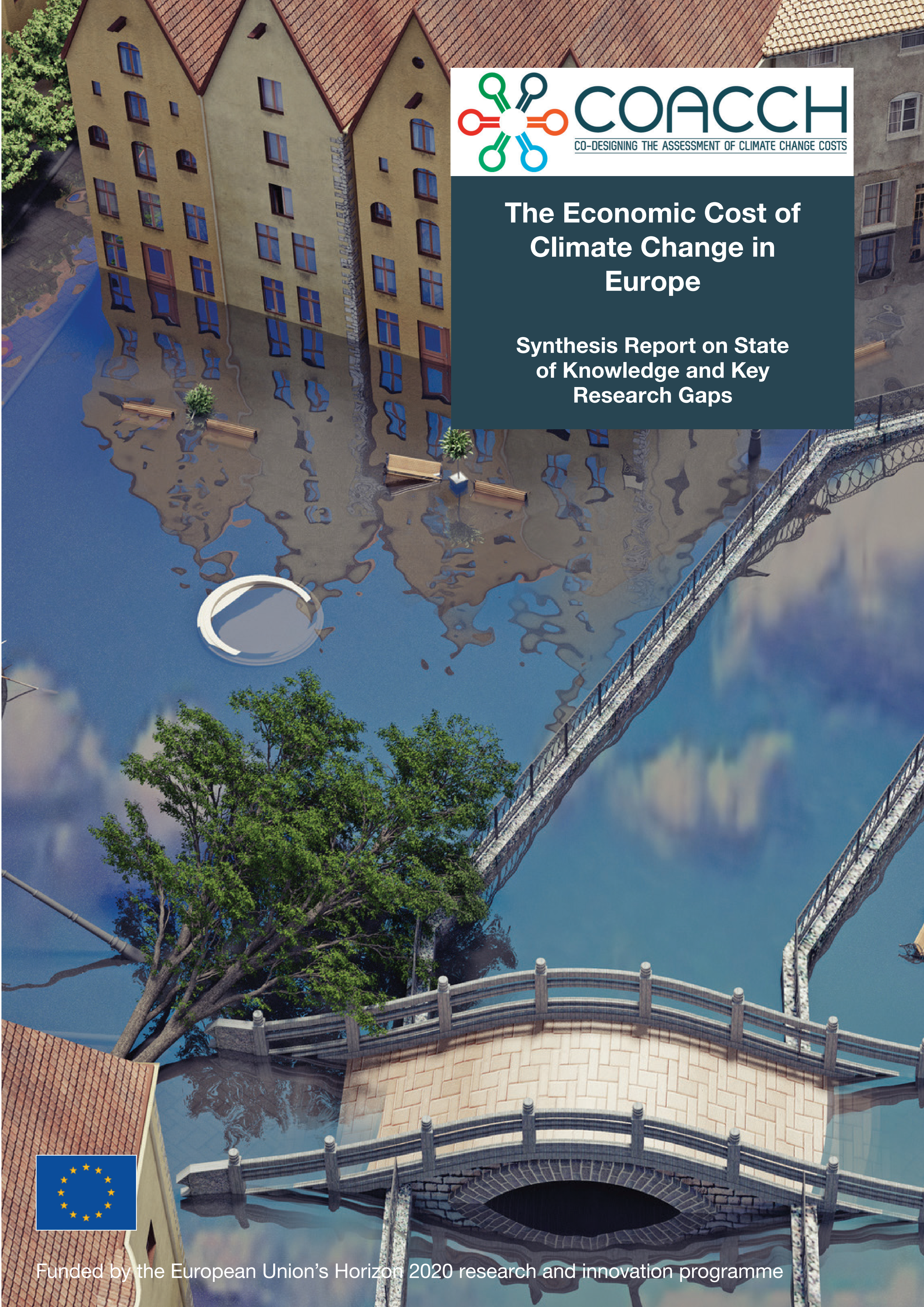

COACCH
CO-DESIGNING THE ASSESSMENT OF CLIMATE CHANGE COSTS

The Economic Cost of Climate Change in Europe

Synthesis Report on State of Knowledge and Key Research Gaps

Funded by the European Union’s Horizon 2020 research and innovation programme

COACCH: CO-designing the Assessment of Climate CHange costs.

The COACCH project is co-ordinated by Fondazione Centro Euro-Mediterraneo Sui Cambiamenti Climatici (FONDAZIONE CMCC), Italy.

To find out more about the COACCH project, please visit http://www.coacch.eu/
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A longer and more detailed version of this report is available as Deliverable 1.2. Available from http://www.coacch.eu/

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Summary

The objective of the COACCH project (**CO**-designing the **A**ssessment of **C**limate **CH**ange costs) is to produce an improved downscaled assessment of the economic costs of climate change in Europe that is of direct use to end users from the research, business, investment and policy making community. To help inform the framing of the project and the first stakeholder workshop, the project has undertaken a review of the current knowledge on the economic costs of climate change in Europe. The findings are summarised in the table below.

Risk / Sector	Coverage of Economic Analysis / Policy	Cost estimates
Coastal zones and coastal storms	Comprehensive coverage (flooding and erosion) of economic impacts at European, national and local level. Applied adaptation policy studies including decision making under uncertainty (DMUU).	✓✓✓
Floods including infrastructure	Good coverage at European, national and local level, especially for river floods (less so urban). Applied policy studies including adaptation / DMUU.	✓✓✓
Agriculture	Good coverage of European and national studies (partial and general equilibrium). Studies of farm and trade adaptation. Emerging policy analysis on adaptation and economics.	✓✓
Energy	Studies on costs of energy demand (heating, cooling) and supply of individual technologies (hydro, wind, solar, thermo-electric). Many policy studies on mitigation. Low coverage on adaptation and system-wide impacts on energy supply.	✓✓
Health	Good coverage of European and national heat related mortality. Some estimates for food-borne disease. Lower coverage for other impacts. Emerging evidence base on adaptation policy (heat).	✓✓
Transport	Some European studies on road and rail infrastructure (extremes). Limited studies for air and indirect effects. Limited adaptation policy analysis.	✓✓
Tourism	European and national studies on beach tourism (Med.) and winter ski tourism (Alps). Low information on nature-based and other tourism. Low level of policy analysis.	✓✓
Forest and fisheries	Limited studies of economic impacts on forestry (productivity). Some studies on European forest fires. No economic studies on pest and diseases. Limited studies of economic impacts on marine or freshwater fisheries.	✓
Water management	Some national and catchment supply-demand studies (and deficit analysis), though lack of European wide cost studies. Limited policy and cross-sectoral adaptation studies.	✓
Business, services and industry	Low evidence base of quantitative studies. Some studies on labour productivity. Limited analysis of economic impacts on supply chains.	✓
Macro-economic analysis	Several pan-European studies using CGE models. Low coverage of effects on drivers of growth, employment, competitiveness.	✓
Biodiversity / ecosystem services	Very low evidence base on economic impacts. Adaptation policy studies limited (only restoration cost studies).	x
Climate tipping points	Some studies of economic costs of major sea level rise in Europe (>1m). Low economic coverage other bio-physical climate tipping points.	✓/ x
Social-economic tipping points	Emerging interest in socio-economic tipping points (migration, food shocks) but no economic analysis	x

Key: ✓✓✓ = High coverage. ✓✓ = Medium coverage. ✓ = Low coverage. x = Evidence gap.

Introduction

Climate change will lead to economic costs. These costs, which are often known as the ‘costs of inaction’, provide key inputs to the policy debate on climate risks, mitigation and adaptation.

The objective of the COACCH project (CO-designing the Assessment of Climate CHange costs) is to produce an improved downscaled assessment of the risks and costs of climate change in Europe. The project is proactively involving stakeholders in co-design, co-production and co-delivery, to produce research that is of direct use to end users from the research, business, investment and policy making communities

This document synthesises the current information on the economic costs of climate change in Europe and identifies areas of possible research to explore with stakeholders at the first COACCH workshop.

Definitions
The following definitions are used in COACCH

Co-design (cooperative design) is the participatory design of a research project with stakeholders (the users of the research). The aim is to jointly develop and define research questions that meet collective interests and needs.

Co-production is the participatory development and implementation of a research project with stakeholders. This is also sometimes called joint knowledge production.

Co-delivery is the participatory design and implementation for the appropriate use of the research, including the joint delivery of research outputs and exploitation of results.

Practice orientated research aims to help inform decisions and/or decision makers. It uses particpatory approaches and trans-disciplinary research. It is also sometimes known as actionable science or science policy practice.

Climate Models and Scenarios

Analysis of the future impacts and economic costs of climate change requires climate models. These in turn require inputs of future greenhouse gas (GHG) emissions, to make projections of future changes in temperature, precipitation and other variables.

Climate models are numerical representations of the climate system and are based on physical properties and feedback processes. Coupled atmosphere/ocean/sea-ice general circulation models, commonly referred to as global climate models (GCMs) provide a comprehensive representation of the global climate system. This modelling has been conducted through a series of Coupled Model Intercomparison Projects (CMIP), the latest of which is CMIP5.

However, these models provide outputs at a high aggregation level: the horizontal resolution of the GCMs involved in CMIP5 was between 100 and 300 km. Therefore, to derive a finer resolution at local-scale, different downscaling approaches are used. Dynamical downscaling uses the output of GCMs to force regional climate models (RCMs) to obtain a finer representation of climate conditions, producing results in the order of 10 km resolution. The Coordinated Regional Climate Downscaling Experiment (CORDEX) and the EUROCORDEX database provides the most recent and highest resolution simulations for Europe, covering the historical period and different future scenarios with different RCMs.

The natural inter-annual variability of weather/climate, which is simulated by these models, requires long time periods to be considered. Climate model results are therefore typically presented for a period of 30 years – the minimum period sufficient to capture this internal variability of the climate system. Note also that the impact of climate change – over and above natural variability – is easier to detect in the signal arising from larger forcings after 2050.

A further issues is that of uncertainty (discussed later). The various global and regional models have different characteristics and therefore an ensemble of model runs is typically used (a group of parallel model simulations).

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Scenarios are used to provide qualitative and quantitative descriptions of how socio-economic parameters may evolve in the future.

These influence the economic costs that arise from climate change, for example, the population affected or the assets at risk. Most studies assess the impacts of future climate change on future socio-economic projections, as a failure to do so implies that future climate change will take place in a world similar to today.

Earlier studies (IPCC 4th Assessment Report) used self-consistent and harmonised scenarios (the SRES scenarios), in which future socio-economic pathways and associated Greenhouse Gas (GHG) emissions were first assessed, then fed into global and European climate models. These scenarios include a medium-high non-mitigation baseline scenario (A1B) and a mitigation scenario (E1).

For the IPCC 5th AR, a new family of scenarios was defined, the Representative Concentration Pathways (the RCPs). These include a set of four new climate (forcing) pathways, which cover futures consistent with the 2°C goal through to high-end (>4°C) scenarios. However, these are not aligned to specific socio-economic scenarios (as in the SRES). Instead the RCPs can be combined with a set of Shared Socio-economic Pathways (SSPs) (see box). This provides the flexibility to combine alternative combinations of future climate and socio-economic futures.

Key Gaps. A key issue for economic analysis – and especially macro-economic analysis – is the need to use consistent and harmonised scenarios in all modelling. As shown in box 1, there are a large number of possible RCP—SSP combinations, and it is common practice to sample across this matrix. COACCH aims to capture the combinations of most interest to stakeholders, thus this is a focus of early engagement.

To provide added policy insight, it is useful to assess the effects of different socioeconomic assumptions on impacts by analysing the same RCP (RCP4.5) for different SSPs. It is also useful to assess the effects of different climate futures, by analysing the same SSP (typically SSP2) under different RCPs. There is also policy insight from understanding the impacts of more extreme climate change pathways.

Finally, there are a number of remaining questions on how to consider climate model uncertainty and how to represent adaptation in the scenarios.

Climate Projections for Europe

The most recent downscale climate projections for Europe are available from EUROCORDEX. These reconfirm that Europe will warm more than the global average, i.e. Europe will experience more than 2°C of warming (relative to pre-industrial levels) even if the Paris goal is achieved in terms of emissions. However, the patterns differ across Europe.

At 2°C of global mean warming, the Iberian Peninsula and other parts of the Mediterranean could experience 3°C of warming in summer, and Scandinavia and the Baltic 4°C of warming in winter. These areas will also reach 2°C of local warming much earlier in time i.e. in the next couple of decades. These trends are exacerbated under higher warming scenarios.

There are also projected increases in extreme events in Europe even for 2°C of global change, which will cause more frequent and severe impacts. This includes increases in daily maximum temperature, extremely hot days and heatwaves over much of Southern and South-Eastern Europe, although relative to current temperatures, there will also be large increases in heat extremes in North-East Europe.

There are also robust model findings of increases in heavy precipitation in Europe, in both summer and winter, with (ensemble mean) intensity increasing by +5% to 15% (and in some areas, even more), even under the 2°C scenario. The projected increase in heavy preciptation is expected also over regions experiencing a reduction of the average precipitation (such as southern Europe). These increases drive the potential increases in flood risk.

The change in average precipitation from different climate simulations varies more by

The Representative Concentration Pathways (RCPs)

The RCPs span a range of possible future emission trajectories over the next century, with each corresponding to a level of total radiative forcing (W/m^2) in the year 2100. The first RCP is a deep mitigation scenario that leads to a very low forcing level of 2.6 W/m^2 (RCP2.6), only marginally higher compared to today (2.29 W/m^2, IPCC, 2013). It is a “peak-and-decline” scenario and is representative of scenarios that lead to very low greenhouse gas concentration levels. This scenario has a good chance of achieving the 2°C goal.

There are also two stabilization scenarios (RCP4.5 and RCP6). RCP4.5 is a medium-low emission scenario in which forcing is stabilised by 2100. Even in this scenario, annual GHG emissions will need to sharply reduce in the second half of the century, which will require significant climate policy (mitigation). Finally, there is one rising (non-stabilisation) scenario (RCP8.5), representative of a non-climate policy scenario, in which GHGs carry on increasing over the century, leading to very high warmings by 2100. Note that achieving RCP4.5 or below always requires mitigation, but more mitigation is required under SSP3 and SSP5. There are also new RCP 2.0 pathways being constructed for a 1.5°C pathway.

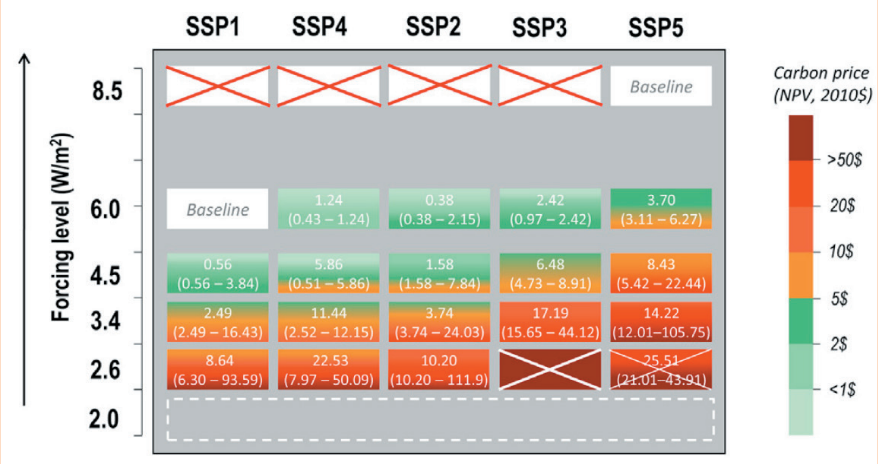
The Shared Socio-economic Pathways (SSPs)

The Shared Socio-economic Pathways (SSPs) provide a new set of socio-economic data for alternative future pathways. They include differing estimates of future population and human resources, economic development, human development, technology, lifestyles, environmental and natural resources and policies and institutions.

Five alternative future SSPs are provided, each with a unique set of socio-economic data and assumptions. SSP2 is the central, Business As Usual (BAU) scenario, as it relies on the extrapolation of current trends. The SSPs are presented along the dimensions of challenges to mitigation and adaptation. For example, in a world in which economic growth is high, there are sufficient resources to adapt, but the challenges in mitigation are high.

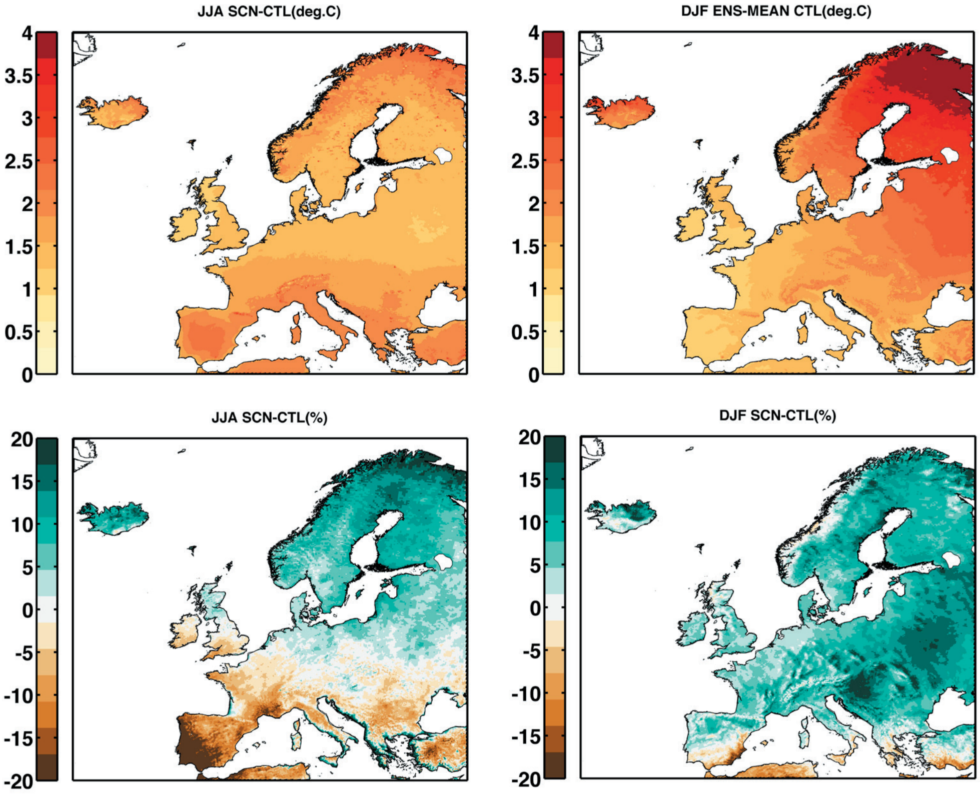
SSP1	Sustainability	Adaptation: low	Mitigation: low
SSP2	Middle of the Road	Adaptation: moderate	Mitigation: moderate
SSP3	Regional Rivalry	Adaptation: high	Mitigation: high
SSP4	Inequality	Adaptation: high	Mitigation: low
SSP5	Fossil-fuel Development	Adaptation: low	Mitigation: high

Combining SSPs and RCPs gives a matrix of possible combinations of socio-economic and climate assumptions. The crosses reflect combinations of SSPs and RCPs that are not likely.



Forcing level (W/m²)	SSP1	SSP4	SSP2	SSP3	SSP5
8.5	☒	☒	☒	☒	Baseline
6.0	Baseline	1.24 (0.43 – 1.24)	0.38 (0.38 – 2.15)	2.42 (0.97 – 2.42)	3.70 (3.11 – 6.27)
4.5	0.56 (0.56 – 3.84)	5.86 (0.51 – 5.86)	1.58 (1.58 – 7.84)	6.48 (4.73 – 8.91)	8.43 (5.42 – 22.44)
3.4	2.49 (2.49 – 16.43)	11.44 (2.52 – 12.15)	3.74 (3.74 – 24.03)	17.19 (15.65 – 44.12)	14.22 (12.01–105.75)
2.6	8.64 (6.30 – 93.59)	22.53 (7.97 – 50.09)	10.20 (10.20 – 111.9)	☒	~~25.51~~ ~~(21.01–43.91)~~
2.0					

Finally, to analyze the effect of mitigation strategies (for specified forcing levels), different Shared climate Policy Assumptions (SPAs) have been identified, which use carbon taxes to achieve the required emission levels.



The increase in seasonal temperature (from 1971–2000) (Top) and Seasonal Precipitation (Bottom) across Europe at 2°C of global average warming. Left (summer). Right (winter).

Average RCM simulated precipitation between the reference period (1971–2000) and period corresponding to global temperature difference of 2°C. Source: Stefan Sobolowski et al, 2014. IMPACT2C project.

model. On average, increases of +10-15% in winter precipitation are projected for Central and Northern Europe for 2°C, and increases in summer precipitation for Northern Europe. At the same time, decreases in summer precipitation, of the order of –10-20%, are projected for Central/Southern Europe.

This is of high policy relevance: even if the 2°C goal is achieved, Europe will still experience large potential impacts.

It is highlighted that these results involve ‘uncertainty’. One unknown factor affecting future climate is the GHG emission path (the future RCP), though this can be considered with multiple scenarios (as above). Another factor is that climate models do not all give the same results, though this can be considered by using different models. It is essential to recognise this uncertainty, not to ignore it or use it as a reason for inaction.

Key Gaps. A key issue, especially for adaptation policy, is the consideration of uncertainty. As well as sampling scenarios, it is therefore common practice to also sample across the climate models. A key issue for the project is therefore to understand the climate information of most interest to stakeholders.

Economic Cost Estimates

The sector studies in this review report monetised impacts in terms of social welfare. This captures the costs and benefits to society, i.e. market and non-market impacts. These estimates are presented in terms of current prices (Euros) for future time periods, without adjustment or discounting. This facilitates direct comparison, over time and between sectors. However, as the review collates information from different studies, some care must be taken in comparing values. The results are from studies that have used different methods, scenarios and time periods. Furthermore, sometimes results are reported as the marginal impacts of climate change (alone), while sometimes they are the combined impacts of future climate and socio-economic change together.

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Coastal flooding

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.

Economic Methods. The economic costs of coastal impacts – and adaptation – are among the most comprehensively covered area of study. Methods for assessing large scale coastal flood risk have developed and been widely applied, at multiple scales, though estimates vary strongly with the sea level rise scenario considered, the digital elevation input data and population sets used, and the consideration of existing protection. For sea-level rise, contributions from ice-sheets add another dimension of uncertainty: even within one RCP scenario there is a large range of possible SLR as the response of the major ice sheets is not understood.

Economic Cost Estimates. A large number of pan-European to national economic studies exist which use integrated coastal assessment models. There are also now an increasing number of detailed national and local scale economic assessments.

In Europe, recent studies using the integrated assessment DIVA model (in the IMPACT2 and RISES-AM projects) estimate the economic costs from coastal flooding and erosion in the EU are €6 to €19 billion per year for RCP2.6, rising to €7 to €27 billion per year for RCP4.5 and €15 to €65 billion per year for RCP8.5 in the 2060s EU (no adaptation, combined climate and socio-economic change (SSP2), no discounting) (Brown et al, 2015).

These costs rise rapidly by the late century, especially for higher emissions pathways. The estimated costs in the EU rise to €18 to €111 billion per year for RCP2.6, €40 to €249 billion per year for RCP4.5 and €153 to €631 billion per year for RCP8.5 by the 2080s. This indicates a disproportionate increase in costs for higher warming scenarios in the second half of the century, and also highlights the benefits of mitigation strategies.

Importantly, there are major differences in the costs borne by different Member States, with the greatest costs projected to occur in France, the UK and the Netherlands (i.e. around the North Sea) if no additional adaptation occurs.

The DIVA model has also been used extensively to look at coastal adaptation and estimate potential costs and benefits. These studies show that adaptation is an extremely cost-effective response, with hard (dike building) and soft (beach nourishment) significantly reducing costs down to very low levels. These show it is economically robust to invest in protection.

The European adaptation cost estimates are complemented by many national and local studies. Some of these indicate higher adaptation costs, in cases where there are high levels of assets at risk (such as in London) or very high standards of protection (the Netherlands). There is also an emerging focus for applied economic studies to use iterative adaptation strategies. The main method applied is the “graphical method” of adaptation pathways. Such analysis identifies adaptation strategies in terms of flexibility, but does not answer the question of economically efficient flexibility and timing of adaptation.

These integrated coastal models have also been used to assess high end sea level scenarios (see tipping points section), which indicate very large increases in economic cost.

Key Gaps. While there are further improvements that can be made to the models, such as with local differentiated sea level rise, improved resolution of population and elevation data, and downscaled consideration of major cities and ports, the main gaps relate to the need to integrate adaptation pathways and decision making under uncertainty into the European-national scale models and strategies. There are also a set of activities to consider the economic, financial and social barriers to adaptation, and to extend the analysis of extreme scenarios to include socio-economic tipping points.

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Flooding and Water

Climate change will affect European regional water cycles, from changes in precipitation, temperature, evapo-transpiration, snow recharge and glacier melt, etc. though with important differences between seasons and locations. This is likely to intensify a number of potential economic risks, including more frequent and/or intense floods, and changes to the water supply-demand balance, water deficits and water quality.

Flooding

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.

Economic Methods. There are a large number of studies of the economic costs of future river floods at the European, national and local scale. Most studies use hydrological models that link flood hazard (extreme flood events) and exposure, then use probability-loss (depth) damage functions to capture the impacts of events of different return periods. These are then integrated into a probabilistic expected annual damage (EAD). These models can also capture existing flood protection and consider adaptation protection levels.

Economic cost estimates. There are several pan-European studies estimating the economic costs of future river flooding in Europe using two major high resolution flood risk models. Roudier et al. (IMPACT2C, 2015a) – using the LISFLOOD model estimated the EAD from climate change will rise from €4-5 billion/year (currently) to €32 billion/year in the EU by the middle of the century (RCP4.5 at 2°C for mean model results, sum of socio-economic and climate change). Earlier LISFLOOD studies (Feyen et al, 2011) found that costs increase significantly for higher emission pathways, especially by the 2080s (with estimates of €98 billion/year by the 2080s for A1B) and also found that uncertainty was large. These studies show an important distributional pattern, with high climate-related costs in some EU Member States. As highlighted by Jongman et al., 2014, these results indicate that the EU Solidarity Fund may face a probability of depletion. However, the LISFLOOD modelling found that adaptation (increased protection) could significantly reduce these damages cost-effectively.

A similar approach was followed by Deltares in the BASE project. The study estimated baseline EAD (1960–1999) at 16 billion Euro, increasing to €26-27 billion by 2030 and €28-33 billion by 2080 (RCP 4.5 and 8.5 respectively), assuming no adaptation (Bouwer et al., 2018).

These models provide valuable insight, at EU and Member State levels. However, they are not accurate enough to provide in-depth estimates of regional and local river flood damages, for which river basin scale models are needed. There are a growing number of such studies being undertaken, for example in countries such as the Netherlands and the UK, and an increasing number of local catchment and city scale studies. There are also important surface water flood risks, especially for urban areas, that are not captured in the studies above and require local modelling. These studies indicate surface water flooding could have similar economic costs to river floods.

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Key Gaps. At the European scale, state-of-the-art estimates of EAD for river floods exist at a high resolution. However, work is still needed to reconcile top-down and bottom-up (local) studies and improve model validation. There is also a need to improve the indirect costs and intangible impacts of flooding and to better represent adaptation (including costs and benefits) in the models. It is stressed that the focus on EAD gives little insight into large extreme events which have high policy resonance, thus there is also a need to further consider these events. A final priority is to advance surface flooding estimates.

Water supply and management

Water supply and wastewater services are vulnerable to climate change impacts. As well as risks to water resources (and possible supply deficits), there are also risks to water infrastructure and water quality, and activities that depend on water (e.g. hydro-power, river transport, power station cooling). However, there are differences in the general trend in precipitation projected for wet and dry regions and differences between wet and dry seasons, and high uncertainty which makes any economic cost analysis challenging.

Economic Methods. Economic studies in the water sector use regional hydrological models, combined with integrated (dynamic) hydrological-economic models. Many studies use integrated assessment (with hydrological and water management models) to consider cross-sectoral demand and supply for catchments. It is also possible to use results in macroeconomic models (partial or CGE) to assess total economic costs.

Economic cost estimates. The high site specificity and the need to consider multiple sources of water demand makes analysis at the European scale challenging. There have been European wide assessments of the impacts of climate change on stream-flow drought, soil moisture drought and water scarcity in the IMPACT2C project (IMPACT2C, 2015), but these were not monetised.

However, there are studies assessing the cost of adaptation in the sector, and these are a proxy for damages. Hughes et al. (2010) estimated adaptation costs for all water services (i.e. water resources, treatment and networks; sewage networks and treatment) at USD ($)110 billion (cumulative) for Western Europe and $104 billion (cumulative) for Eastern Europe, in the period 2010–50. The EC (2009) also reports that the cost of desalination and water transport in 2030 could range from €8.5 to 15 billion annually. A further study (Mima et al, 2012) estimated the additional costs of increased electricity demand for water supply and treatment (due to increasing water demand from climate change) at €1.5 billion/year by 2050 and €5 billion/year by 2100 for the A1B scenario, falling significantly under an E1 scenario.

There are also economic studies at national or catchment level. For example, at the country level, the Bank of Greece (2011) calculated the cost of climate change to the water supply sector, estimating the cumulative cost from climate change at 1.3% of GDP by 2050, increasing to 1.8% by late century (A2 scenario).

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).

Economic Methods. There is a large body of literature on the slow onset impacts of climate change on production, but less research into variance and extremes. 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

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used to assess some adaptation options (farm level options and trade).

Economic cost estimates. There have been numerous studies analysing production changes in Europe, though not so many studies on economic analysis. The results of crop modelling studies tend to show a strong distributional pattern in Europe, with productivity gains in the North and losses in the South.

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 would reduce GDP by 0.3%. The study reported strong distributional patterns, with small productivity and economic gains observed in the Northern European regions 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. In the short-term, the study found technical adaptation could address yield reductions for all of Europe (apart from the Iberian Peninsula).

The ECONADAPT project assessed market driven (autonomous) adaptation around demand and supply responses using a global multi-sector CGE model, which included agriculture (Ciscar et al, 2016). At the global level, market-based adaptation reduced climate damages by a third for both GDP and welfare losses. The analysis in Europe found that market driven benefits were greatest in Northern Europe, but smaller in Southern Europe, reflecting the size of impacts and potential for substitution.

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.

The results of these economic studies vary with the climate, crop and economic models used and key assumptions made (CO_2 fertilisation, interplay between sectors) and on international effects (demand, supply and trade). A major inter-comparison initiative (the Agricultural Model Inter-comparison and Improvement Project, AGMIP) investigated these issues. This found that climate change could lead to a 20% (mean) food price rise in 2050 globally, but with a large range (0% to 60%) (Nelson et al., 2014). Yield losses and price impacts rise more sharply in later years under higher warming scenarios.

Key gaps. The main focus to date has been on medium to long-term productivity changes and studies have not analysed inter-annual price fluctuations, e.g. from extreme weather events. There has also been less coverage of what happens when yields and prices diverge away from market equilibria. Most studies tend to focus on the optimisation of welfare or profit along a single pathway for a single scenario and further work is needed on uncertainty (multiple futures and costs) and robust adaptation responses. For mitigation policy, a key consideration is the interaction between agriculture, forestry and bio-energy. Finally, further research on unexpected shocks in agricultural supply and markets, as well as long-term tipping points, are also a priority.

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Forestry and Fisheries

Forestry is a sector with long life-times, and so potentially at 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, affecting vulnerability to secondary impacts, and from increasing forest fires, affecting managed and natural forests. Climate change will also impact marine 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 human fishing activities are the dominant factor for commercial fisheries, climate change will add additional pressure.

Economic Methods. For forestry, there are a number of European (and Global) impact models (Dynamic Global Vegetation Models), but analysis is challenging due to the variety of locations, landscapes and tree species. The results of these models can be fed into partial equilibrium models, such as the Global Forest Model – G4M. The main approach used for fisheries is physical modelling, using either ecological trophic modelling, statistical analysis, statistical forecasting, time-series analysis, or coupled modelling approaches.

Economic cost estimates. There is relatively little economic analysis of the impacts of climate change on forestry and fisheries.

Forests. The warming climate in Europe will shift the suitability of forest species and this will have economic consequences. Hanewinkel et al. (2013) estimated the impact from future temperature increases in Europe by 2100, analysing 32 tree species (A1B, B2 and A1F1). The analysis found the expected value of European forest land will reduce due to a decline in economically valuable species. Depending on the scenario and discount rate, this indicated a 28% reduction (with a range of 14% and 50%) in the present value of forest land in Europe, with a cost of 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).

Recent events in North America have highlighted the high economic costs of invasive pest and pathogens. In Europe, the combination of increased forest stress and changing climate suitability is expected to increase risks, though as yet, there are no economic assessments.

Regarding **fisheries**, there are several global and regional studies on changes in annual catch and the redistribution of stocks or catch potential. These tend to find that productivity will increase in high latitudes and decrease in mid-low latitudes. Cheung et al. (2010) estimate an average 30–70% increase in global catch in high-latitude regions but a drop of up to 40% in the tropics by mid-century. Some studies suggest changes may be happening already in important European fisheries. There is less information on the economic impacts of climate change on freshwater fisheries and aquaculture.

Key gaps. There is a need for further economic analysis of impacts on production, consumption and markets for forestry products, as well as land-use interactions with the agriculture sector. There are gaps on the economic costs on wildfires, changes in pests and diseases and on wider ecosystem services, as well as large-scale tipping points. There are also many gaps for fisheries, with a need to advance the economic modelling on marine fisheries and aquaculture production, and to better understand key effects such as ocean acidification.

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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 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.

Economic Methods. Most studies and methods focus on extreme weather phenomena. A number of studies extend flood risk modelling (detailed earlier) to look at transport related damages, and in some cases, extend these to look at travel time disruption. Other methods look at the potential threshold levels above which damage occurs, then assess the change in threshold exceedance and monetize infrastructure damage, accident costs and delay. Analysis of major events can be considered using transport network models, input-output models or using wider economic analysis.

Economic cost estimates. There are a growing number of studies in this area, across various modes of transport, though it is stressed that climate change has different effects on road, rail, air and water transport, as well as intermodal terminals.

The WEATHER project estimated that the total costs from extreme weather events are currently €2.5 billion/year in Europe (1998–2010). These are dominated by road transport (€1.8 billion/year 72%), followed by air (€0.4 bn/year 14%) and rail (€0.3 bn/year 12%) (Enei et al., 2011). The project estimated climate change will increase these costs by 20% by 2040–2050 (EEA, 2017). For road transport, the costs from heat stress and flooding are large, but are offset by a large reduction in winter maintenance cost, thus the net increase is 7%. For the rail sector, heat stress and heavy rainfall are estimated to increase costs by 72%. The impacts on air transport are very uncertain because they result from extreme wind and fog, but are estimated to increase by 38% (Przyluski, et al. 2012). For inland waterways, the main issues are low river flows, from drier summers. Case studies for the Rhine and Danube show these are a possible long-term issue, increasing unit transport costs due to the switch to smaller vessels and modal shift (Doll et al, 2014).

The PESETA II study (Ciscar et al., 2014) considered impacts on the road and rail network in Europe, estimating the total damages to transport infrastructure due to extreme precipitation at €930 million/year by the end of century under an A1B scenario (around a 50% increase from the current baseline damage of €629 million/year) and €770 million/year under a 2°C scenario. More specific estimates also exist for road transport. The future costs are driven by future socio-economic assumptions, i.e. transport patterns and demand.

The EWENT project also estimated current and future weather-related costs on transport. It estimated current costs are €18 billion/year (2010). This is higher than the studies above due to a broader classification of weather events, inclusion of operation and logistical costs, and higher accident levels and thus costs. It projected an increase of €2 billion/year by 2040–2060 due to climate change. For rail transport, an increase of €117million/year was projected between 2010 and 2040–2070 (Nokkala et al., 2012).

Finally, the JRC study on critical infrastructure (Forzieri et al. 2018) estimated the multi-hazard, multi-sector damage due to climate change for the European transport sector will rise from €0.8 bn. today to €11.9 billion by the 2080s due to climate change. All European regions are projected to experience an increase, though the climate drivers differ, e.g. droughts and heatwaves dominating in Southern and South-Eastern Europe.

Key Gaps. The main research priorities are to improve the direct cost estimates for road transport and the costs of flooding for rail transport. Further method development is also needed to assess the indirect costs of transport disruption (for rail and road). Other priorities include the economic costs of climate change on critical transport infrastructure, including inland and marine transport hubs, and the analysis of indirect network effects. Further work is also needed to advance cost-benefit analysis for adaptation investment decisions.

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Tourism

While the overall demand for tourism will continue to increase over the next few decades, the distribution, timing, and type is expected to shift as a result of climate change. Currently, summer tourism in Europe is focused on the Mediterranean where it accounts for over 10% of GDP. Increasing temperatures, heat waves and availability of water may have negative effects for tourism (and expenditures) in these regions, leading to a shift to more northerly locations (redistribution). Sea level rise, coastline retreat and erosion may also affect beach and coastal recreation.

For winter tourism, changes in snow availability and other factors will impact the length and quality of the European season. Those resorts at lower altitudes will have higher costs (artificial snow) in the short term and their economic viability may be threatened in the long term, although impacts could be offset by summer tourism.

Economic Methods. Quantitative evaluation of climate change effects on tourism include physical changes, often with the use of climate indexes, as well as tourism demand modelling based on revealed preferences. The majority of studies assess beach tourism using the Tourism Climate Index (TCI) and cost changes in tourism expenditure. Other approaches include the use of econometric analysis, partial adjustment models, hedonic price models and integrated CGE models.

Economic cost estimates. Several studies have assessed the potential economic costs for summer and winter tourism in Europe.

Amelung and Moreno (2012) estimated the cost of climate change on tourism in Europe. They identify large differences in results depending on whether future socio-economic change (i.e. rising demand) is taken into account, but identify a strong redistribution of summer tourism away from Southern Europe.

The PESETA II study (Ciscar et al., 2014) estimated the costs of climate change on tourism (the fall in revenues) at €15 billion/year by the end of the century (A1B). A further analysis in this study (Barrios and Ibañez Rivas, 2013) used a travel cost approach and hedonic valuation of recreational demand and amenities and reported that climate change could decrease tourism revenues by 0.31% to 0.45% of GDP per year in southern Europe (but with Northern Europe and central Europe gaining).

Perrels et al, (2015) also assessed regional tourism revenues from beach summer tourism in Europe by mid-century finding similar patterns to the studies above. They also investigated supply-side adaptation and conclude that warmer regions will see a shift to shoulder seasons, while cooler regions will shift towards the peak season.

There are also studies of the impacts of climate change on winter tourism in Europe. In the short term these include additional costs from increased use of snow machines (OECD, 2007: Damm et al, 2017). In the medium term, there will be impacts from the reduced snow cover and conditions, especially in low-lying ski areas. Using time series regression models for a +2°C scenario, Damm et al. (2017) estimated the maximum weather-induced risk of losses in winter overnight stays in Europe at up to €780 million per season.

Key Gaps. There has been a focus on summer beach tourism to date, though there are still gaps, such as the integration of multiple climate impacts (productivity, coastal impacts, water) alongside temperature. There is a major gap for other tourism sectors, with further development for winter tourism and new analysis for nature based and other tourism types. There is also further analysis needed for adaptation strategies and costs.

Business and Industry, including Trade and Insurance

Climate change impacts such as floods, as well as high temperatures and water availability, will all have an effect on business and industry. However, the balance of risks will vary with sub-sector and location, and sites and operations will be affected in different ways. Risks also extend along supply chains,

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with impacts in non-European countries affecting the production and transport of raw materials and intermediate goods. There will also be shifts in demand for goods, services and trade as a result of climate change. All of these may affect business costs, profitability, competitiveness, employment and sector economic performance.

While climate change will affect all aspects of business, there has been a particular focus on insurance, because it is climate sensitive and because it has a role in supporting adaptation to extreme events. There are different insurance models across the Member States, but there will be increasing climate challenges for national insurance systems and global reinsurance, resulting in increasing premiums, decreased coverage or increased moral hazard.

Economic Methods. There are four approaches in the literature used to assess the impacts of climate change on business and industry: (i) qualitative assessments, (ii) indicator-based assessments, (iii) supply chain risk assessments, which can include input-output analysis or network analysis and (iv) macro-economic assessments. There is also an analytical modelling base for disasters and the insurance sector. At the aggregate level, a number of insurance and economic catastrophe models have been used to assess and stress-test the impact of high-level climate-related events on national and pan-European insurance and funds.

Economic cost estimates. In general, there is a low evidence base on the economic impacts of climate change on business and industry.

There have been assessments of the impacts of climate change on labour productivity (sometimes reported as occupational health). Earlier work focused on the impacts on outdoor work, as work rates decline with rising heat and humidity. Kovats et al (2011) estimated Southern Europe would incur a mean loss of productivity (days lost) – of 0.4% to 0.9% by the 2080s, with total productivity losses for the EU of €300 – 740 million (A1B). Recent updates (Lloyd et al, 2016) extend productivity losses to three sectors: agriculture, industry, and service, taking account of different work intensities. By the 2050s, they estimate a 0.4% increase in labour time lost for southern Europe, and a 0.2% increase for central Europe South. Productivity losses have also been estimated in CGE analysis at the European and global level (Ciscar, 2014; Dellink et al. 2017) and in more depth at the national level (Steininger et al. 2016 in Austria).

There have been some studies of supply chain and procurement risks, focusing on disruptions and delays in delivery and transport due to extremes (Lühr et al., 2014). There has also been analysis of supply chain risks using input-output models (Wenz and Levermann, 2016) and the risks of climate change on embodied water in imports (Hunt et al., 2014). Several studies indicate that the indirect effects of climate change internationally could be as large as the direct impacts within Europe. The ImpactChain project (in Germany) estimates that imports from non-EU regions could decline by up to 2% by 2050 but also that exports to non-EU regions could decline by up to 0.3%, leading to a reduction in national GDP and welfare despite higher EU trade. There have also been a number of case studies on specific regions and sectors, such as the impact of losses in the automobile industry from flooding in Thailand in 2011 (Haraguch and Lall, 2015).

There are several studies that have looked at insurance. As an example, the ENHANCE project looked at the financial stress from increasing flood risk in the EU (Jongman et al., 2014), finding that with climate change, the EU Solidarity Fund has a substantial and increasing probability of depletion (insufficient funds).

Key gaps. This remains an area of low coverage and there are numerous research priorities. There is further work needed to investigate supply chain effects, both in Europe and internationally. The analysis of trade implications on business – extending to macro-economic analysis and the effects on public budgets – is also of interest. The analysis of shocks and tipping points on businesses is also an important research gap. For insurance, the further analysis of climate change on EU insurance arrangements is considered a priority.

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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. They will lead to economic costs and benefits, noting cooling is predominantly powered by electricity, while heating uses a mix of energy sources. These future changes need to be seen in the context of socio-economic drivers and especially mitigation policy. 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).

Economic Methods. At the European and national level, there are large number of energy models already in use, including least cost energy modelling and general equilibrium models, as well as studies that use econometric analysis. These can be extended to take account of changes in heating and cooling demand, typically by assessing the impact of climate change on heating and cooling degree days.

Economic cost estimates. There are economic costs studies on the effects of climate change on both energy demand and supply in Europe.

Mima et al. (2011) assessed the costs of additional cooling for residential and commercial sectors in Europe using a partial equilibrium model of the energy system, assessing the marginal costs of generation. These indicate large increases in cooling costs, estimated at around €30 billion/year in EU27 by 2050, rising to €109 billion/year by 2100 (A1B scenario). These fall to €20 billion/year under an E1 scenario. These costs had a strong distributional pattern, with large increases in Southern Europe. The study projected a similar level of economic benefits from reduced winter heating demand, though these primarily arise in North and North-West Europe.

The PESETA II study (Ciscar et al, 2014) estimated overall EU energy demand could fall by 13% by 2100 (A1B) due to reduced heating requirements. It projected reductions in energy demand except in Southern Europe, where the need for additional cooling increases demand by 8%. Under a 2°C scenario, the demand reductions are lower. Similar findings, with an overall reduction in aggregate total final demand for Europe, were found by De Cian and Sue Wing

On the supply side, there have been several studies on the effects of climate change on hydro-power generation. For Europe, most studies show a positive effect for northern Europe and a negative effect for South and Eastern Europe, though the overall change varies across studies from almost no effect to decreases of 5-10% by the end of the century.

Tobin et al. (2014) assessed the potential impacts of climate change on wind generation, finding that mean energy yields will reduce by less than 5% by 2050 (2°C scenario), and as part of the same study Vautard et al. (IMPACT2C, 2015) found limited changes in photovoltaïc power potential and plants yields.

A number of studies have looked at the impacts of climate change on power plant cooling water and the reduced efficiency of thermal power plants (nuclear and fossil). Mima and Criqui (2015) estimated that thermal and nuclear power generation could be reduced by up to 2-3% (thermal) and 4-5% per year (nuclear) for current plant (A1B) though changes in plant design would reduce these significantly. The TopDAd study assessed these impacts for nuclear power in France and estimated losses could vary between tens and several hundred billions of euros per decade by 2100 (for current infrastructure and policies), but adaptation strategies can reduce the losses significantly.

Key Gaps. While there are some studies, a major gap still exists on cooling demand, including extremes and the costs and benefits of adaptation options for cooling. There are gaps remaining also on the economic costs of extremes on hydropower, wind, and thermal generation, and overall energy security.

Health

There are a number of health impacts from climate change. These include direct impacts,

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such as heat-related mortality, deaths and injuries from flooding, etc., but also indirect 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.

Economic Methods. There are a number of studies that have quantified and valued the impacts of climate change on health in Europe. These use impact assessment, subsequently valuing the total effect on society's welfare in terms of the resource (treatment) costs, opportunity costs (lost productivity) and dis-utility (from willingness to pay studies).

Economic cost estimates. The most studied health impact in Europe is heat-related mortality (Watkiss and Hunt, 2012: Kovats, 2011: Ciscar et al, 2014). The most recent study (Kendrovski et al. 2017) estimated an additional 23 thousand attributable deaths at 2°C of warming (mid century) in Europe, with estimated economic costs of € 41 billion/year (using the VSL, two thirds due to the climate signal), increasing strongly under high emission later in the century. The highest impacts were found in Mediterranean and Southern Eastern EU countries. Values from these studies differ considerably according to whether a full Value of a Statistical Life (VSL) or a Value of a Life Year Lost (VOLY) approach is used (Chiabai et al., 2018.), though assumptions of acclimatisation are also important.

These studies also do not include early adaptation, including heat alert systems. Recent analysis shows these have very high benefit to cost ratios, but do not completely reduce all heat related impacts (Hunt et al, 2016: Sanderson et al, 2018).

Climate change will also reduce future cold-related mortality in Europe, but these benefits have been less studied. Earlier studies indicate (Watkiss and Hunt, 2012) that cold related benefits from climate change are at least as large as heat related impacts at the European level, though with a different geographical distribution.

There have been a number of studies on climate and food-borne disease, notably salmonellosis. Kovats et al (2011) estimated welfare costs of €68 to €89 million/year in the 2050s and 2080s respectively, for the EU, falling to €46 to €49 million/year if a decline in incidence (due to better regulation) was included. A latter study (IMPACT2C, 2015b) estimated resource costs for additional hospital admissions and additional cases of salmonellosis and campylobacteriosis at around €700 million in 2041–2070 period for the A1B scenario and around €650 million in the E1 scenario.

There are also fatalities and injuries from climate induced increases in coastal flooding, river flooding and wind storms. The potential impacts of coastal floods in Europe (Kovats et al, 2011) were estimated at €151 million/year in the 2050s rising to €750 million/year by the 2080s, but were significantly lower under a mitigation scenario (and lower still under an adaptation scenario). There has been less analysis of climate related health impacts from river flooding and storms, though some country analysis of increased mental illness post-disaster at the national level (Hunt, 2012).

Climate change will also change the prevalence and occurrence of some vector-borne diseases (VBDs), notably infections transmitted by arthropods. In Europe, tick-borne diseases (Tick-borne encephalitis (TBE) and Lyme disease) are the key concern, however, there are no valuation studies to date (though some studies of adaptation costs [vaccinations]). There are risks of mosquito borne disease increasing, such as malaria, dengue fever and chikungunya, but these risks are considered low due to effective vector control measures.

Finally, climate change will affect air quality. These impacts were quantified (IMPACT2C, 2015b) and found to be low for ozone, but potentially high but uncertain for particulate matter. There is a further risk of changes in aeroallergens, such as pollen concentration, volume and distribution, but quantified estimates are lacking. There are much larger economic benefits from mitigation policy, from air quality and health co-benefits, estimated in analysis of European 2030 climate and energy policy (e.g. Ščasný et al., 2015).

Key Gaps. To date, most focus has been on heat related mortality, though important issues remain in this area with regard to valuation, distributional impacts (between north and south), hot-spots and adaptation strategies. There are key gaps in relation to vector borne disease and aero-

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allergens, a need to understand the potential impacts on health services and social care, and to consider possible health tipping points.

Macroeconomics, growth and competitiveness

A number of studies consider the wider economic costs of climate change in Europe and globally. These can investigate the relationship between climate change and the economic performance of countries, most commonly represented by indicators of competitiveness, GDP and, in broader terms, growth. This is a step beyond the aggregation of costs at the sectoral level, as it aims to identify the interactions across different impacts, and the economic reaction and transmission channels (including market-driven adaptation). It also can assess how these interactions affect the overall capacity of country economies to produce goods, services and ultimately "welfare".

Economic Methods. The macro-economic effects of climate change can be assessed by feeding sector results into economy-wide simulation models, such as computable general equilibrium (CGE) models. These have the advantage of capturing the whole economy (sectors, domestic and international interlinkages) and can analyse impacts on national production, welfare and GDP, however, it is often challenging to represent impacts and these models omit non-market effects. More recently, there has been a focus on coupled assessments, linking process-based models (i.e. those determining climate change induced losses in crop yields, land loss due to sea-level rise etc.) to CGE models. It is also possible to use econometric analysis, establishing past relationships between climate and the economy, then applying these to future climate change. Finally, there are global and continental economic estimates provided by "hard-linked" integrated assessment models (IAMs). These provide a self-consistent integrated analysis of emissions, climate change, impacts and economic effects, including both market and non-market impacts. They report aggregate economic impacts as a % of GDP, through simplified and compact damage functions, rather than undertaking full macro-economic analysis.

Economic cost estimates. A number of studies have used CGE models to assess the macro-economic costs of climate change. The PESETA II study (Ciscar et al., 2014) estimated the total damages from climate change in the EU at €190 billion/year for an A1B scenario (a median temperature increase of roughly 3°C by the end of the century) by the 2080s, with a net welfare loss equivalent to 1.8% of current GDP. These impacts fell to €120 billion/year under a 2°C scenario. There was a strong distributional pattern with high impacts in southern regions. Overall welfare impacts were dominated by health effects.

The OECD (2015) also used a CGE model to estimate the economic costs of climate change through to 2060. Their central projection estimated global damages of a 1.5% GDP loss by 2060, but found lower damages in Europe, as agricultural benefits from enhanced trade offset coastal, tourism and health impacts. This study was updated (Dellink et al. 2017) using a production function approach, which estimated global GDP losses at 1.0 – 3.3% by 2060.

There have also been a number of regional and national assessments. The CIRCE project (Navarra and Tubiana, 2013) estimated climate costs in the Mediterranean focusing on tourism, sea-level rise and energy demand patterns using a CGE model, and reported losses of 1.2% of GDP by 2050 (A1B). A macro-analysis in Greece (BoG, 2011) estimated GDP could fall by 2% by 2050 and 3-6% by 2100, largely due to climate change impacts on tourism. A recent study in Austria (Steininger et al., 2016) estimated current welfare costs of climate extreme events at €1 billion/year, rising with climate change to €4–5 billion/year by mid-century, but highlight large tail-end events could increase annual damages to €40 billion.

One study (Triple E Consulting 2014) used the EXIMOD model to quantify the impacts of climate change on employment in EU sectors. This estimated 240 thousand and 410 thousand job losses by 2020 and 2050 (no adaptation), respectively, finding distributional differences (gains in the North and losses in the East). There are, as yet, no quantified studies on competitiveness.

Finally, an emerging issue is whether climate change might actually affect the drivers of

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growth (and growth rates), not just levels of outputs, and how much modelling approaches are able to capture this. For instance, the econometric literature (Dell et al. (2012) and Burke et al. (2015)) suggest that climate does have a negative effect on growth (at least in less developed countries) and report economic costs that are much larger than the CGE studies mentioned above. When this issue has been assessed with GCE models (notably OECD, 2015), impacts on growth have been detected, but they are (relatively) modest.

Key Gaps. There is a need to develop consistent and harmonised European economic cost estimates, including disaggregated estimates at national and subnational levels. This requires improving the interlinkages between process-based and sector analysis and the CGE models. Additional priorities include analysis on the impacts of climate change on growth rates (drivers of growth) and analysis of sectoral differences and changes in the level of competitiveness. Further research priorities include the integration of trade and market effects, as well as representation of major extremes and tipping points.

Biodiversity and Ecosystem Services

Climate change poses very large risks to terrestrial, aquatic and marine biodiversity and the ecosystem services they provide (provisioning, regulating, cultural and supporting services). It will shift geographic ranges, seasonal activities, migration patterns, reproduction, growth, abundance and species interactions, and will increase the rate of species extinction, especially in the second half of the 21st century (Settele et al., 2014). As well as terrestrial ecosystems, there are potentially large impacts on marine ecosystems, including from ocean acidification, ocean warming and sea-level rise, as well as impacts on freshwater ecosystems (rivers and lakes).

Economic Methods. This remains one of the most challenging areas for economic cost analysis. There is a lack of quantitative studies on the physical impacts of climate change on biodiversity and ecosystem services, making it difficult to undertake subsequent costing. Where information on impacts does exist, these are generally not captured by market prices, which makes valuation challenging. Non-market measures of the willingness to pay (to avoid impacts) can be used, though these are highly specific and are difficult and resource intensive to obtain, though the valuation literature has been advanced under The Economics of Ecosystems and Biodiversity initiative (TEEB, 2009: TEEB 2010). There are also challenges for valuation given the risk of non-marginal changes.

Economic cost estimates. Impact cost studies are very rare at the European and national level. Tietjen et al. (2010) used the Lund-Potsdam-Jena Dynamic Global Vegetation Model for managed Land (LPJmL) to assess changes in natural and managed vegetation under climate change, then mapped existing Willingness To Pay (WTP) results from TEEB to the changes in ecosystem services identified. However, as the study only captured vegetation shifts, the resulting costs were modest.

There are some national studies (Berry and Hunt, 2006) that have looked at potential costs using a replacement cost approach to value changes in habitat coverage, linking model outputs for species and habitats of national and regional significance, including some which have a direct economic value.

There have been some very indicative macro-economic modelling studies of climate change on biodiversity and ecosystem services. Palatnik and Nunes (2014) examined the climate-change-induced impacts on biodiversity in the agricultural sector in terms of changes in agricultural land productivity. OECD (2015) undertook a global economic analysis, with regional disaggregation. They modelled changes in terrestrial mean species abundance as an indicator of biodiversity and valued biodiversity loss using a function that relates expenditure to temperature change. The cost estimates for EU countries under these scenarios were large, estimated at 0.5% to 1.1% of GDP (RCP6 and RCP8.5, respectively).

Key Gaps. There are very large gaps in this field, starting with estimates of physical impacts, and including all aspects of the economic valuation of biodiversity and ecosystem services. More underlying work is needed to understand risk, at the spatial disaggregated level across Europe, and to develop WTP estimates. There is also a need to include climate alongside other drivers of change. A final issue is the consideration of possible non-marginal impacts and tipping points.

Climate Tipping Points

Tipping points relate to critical thresholds at which a small perturbation can alter the state of a system. A number of global tipping elements have been identified, which could pass tipping points as a result of climate change, leading to large-scale consequences. These may be triggered by self-amplifying processes (feedbacks) and they can be potentially abrupt, non-linear and irreversible.

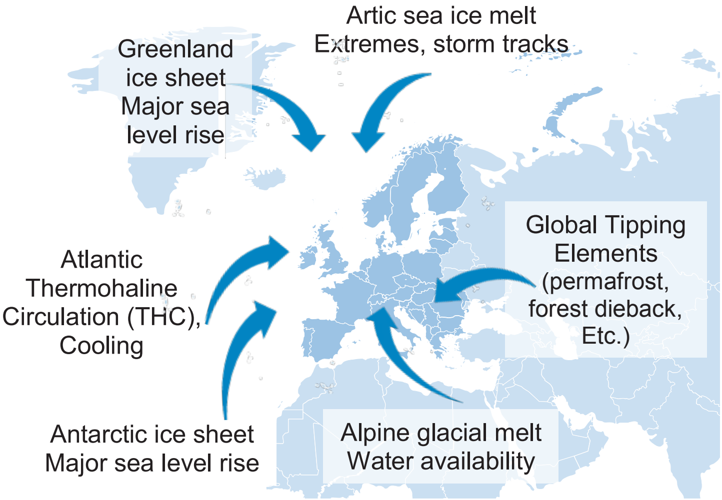
These 'bio-physical' climate tipping points provide a key justification for global mitigation policy, yet they are poorly represented in economic assessments of climate change. Lenton et. al. (2008) compiled a list of global tipping elements and Levermann et al. (2012) identified the most important for Europe. Several studies make indicative estimates of the warming levels (°C) that might trigger these events.

Based on current literature, two tipping points are likely to be exceeded in the short term. Artic summer ice is projected to disappear at warming of 1–2°C (though winter sea ice will not likely disappear until 5°C). This does not affect sea levels, but it will influence Atlantic storm tracks into Europe and could be associated with cold winters and increased probability of extreme cold events. It will also have major impacts on Artic ecosystems, though with potential benefits of shorter navigation times and access to Artic resources. Alpine glacier melting will occur with warmer temperatures, accelerated by ice-albedo feedback. Models project that at 2°C of warming (+3–4°C locally) there could be an almost complete loss of glacier ice in the Alps. This will affect water availability as glaciers shrink. In the short-term, flows may increase with melt water, but in the longer-term, the seasonal buffering will decline and summer river flows are projected to fall, affecting water availability, hydropower and stability (landslide risk).

There are also risks from rapid sea level rise (SLR) in this century and beyond, with previous tipping point studies identifying the accelerated melt of the Greenland Ice Sheet (GIS) and/or the accelerated melt / possible collapse of the (West) Antarctic Ice Sheet (AIS). The water stored in these would raise global sea levels by about 7 m (GIS) and 5 metres (WAIS), although such increases would take millennia. The tipping points for the onset of these events are uncertain, though more likely to be above 2°C. Nevertheless, recent modelling has shown that the mass loss of the AIS could be very sensitive to temperature rise and mitigation targets: under high (8.5) RCP scenarios and with certain instability processes, the AIS could contribute around one metre by 2100 and about 15 meters by 2500 to global-mean sea-level rise (DeConto and Pollard, 2016).

In the longer-term, climate change may also trigger a weakening or even collapse of the Atlantic Thermohaline Circulation (THC), resulting in a large temperature decrease in Northwest Europe, as well as reduced precipitation and local sea level rise. The tipping point for this event is complex, and although it is very likely to weaken, an abrupt transition or collapse is considered very unlikely over this century (Stocker et al, 2013).

Finally, other global tipping elements could affect Europe, for example with accelerated warming due to permafrost melting or major forest dieback, as well as impacts from tipping point changes in regional weather systems (in other parts of the world) affecting Europe indirectly.



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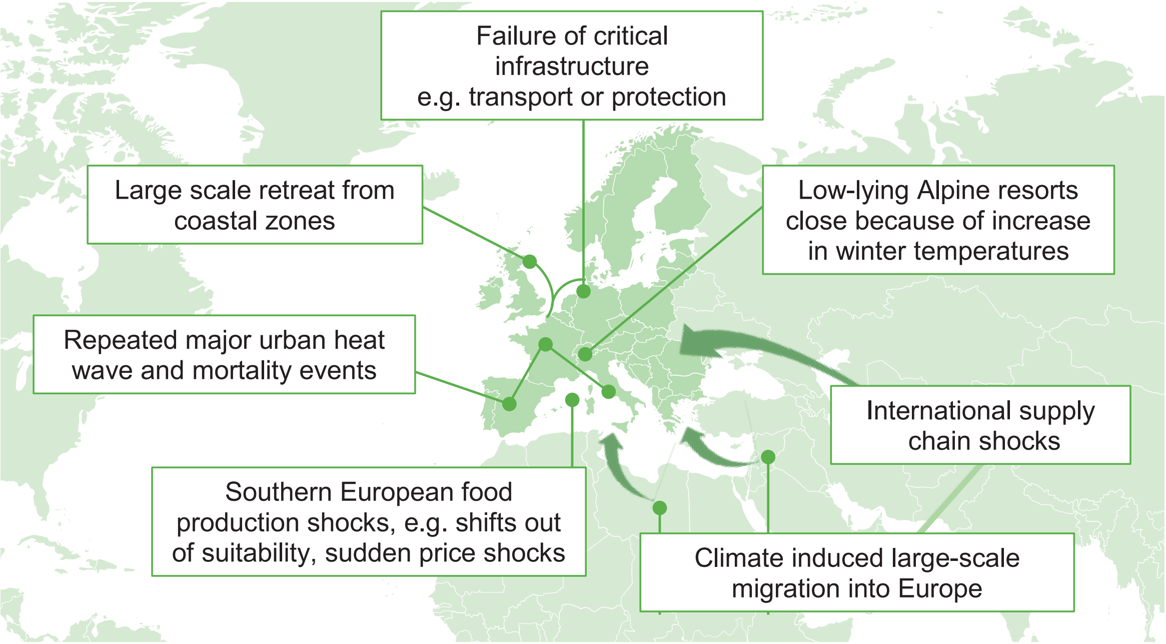
Economic Cost Estimates and key gaps. The entire field of tipping points is a priority for economic research. There are a small number of studies of high SLR scenarios for Europe, which use the existing integrated models (see coastal section). Brown et al (2012) estimated the economic costs of 1.4 metres in the EU at €156 billion/year by the 2080s – which was found to be six times higher than the economic costs of the A1B scenario. The recent RISES-AM study estimated that with 2.5 metres of sea level rise, the 21st century cumulative economic costs in Europe could rise to €18.8 trillion (without additional adaptation), approximately equivalent to today's EU GDP. Lontzek et al. (2015) estimated damages of 10-20% of world GDP for a collapse of the THC and there are some studies using stochastic Integrated Assessment Models (Lontzek et al., 2015, Cai et al., 2016).

Socio-economic tipping points

The COACCH project is developing a new concept of socio-economic tipping points. This idea recognises that even gradual climate change may abruptly and significantly alter the functioning of socio-economic systems, which can lead to major economic costs. These changes may arise directly in Europe, but may also involve global events that spill-over into Europe.

It is more difficult to translate the strict definition of tipping points into the socio-economic domain, and there are different types of pathways that may occur. These may involve a case where climate change triggers a large-scale socio-economic event (a major shock). It might also involve climate change (above a threshold) affecting the functioning of an established socio-economic system. Either of these might involve feedback loops (and amplification), and they could be non-linear and irreversible. They could therefore trigger a rapid increase in costs, e.g. as measured by a large drop in the GDP of a region, or they may require a fundamental new functioning of an existing system with high associated costs.

Key Gaps. Socio-economic tipping points are an emerging concept. The COACCH project is seeking stakeholder inputs on socio-economic tipping points of interest, as part of the co-design process. These are likely to include different types of tipping points, of interest to different stakeholders. For example, a European policy maker might be interested in large-scale pan-European shocks, while a national stakeholder might be interested in smaller-scale or regional events. In contrast, a business stakeholder might be concerned when climate change requires a transformative shift in business operations. The figure below gives some illustrative examples.



Illustrative Socio-Economic Tipping Points

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Findings and Policy Insights

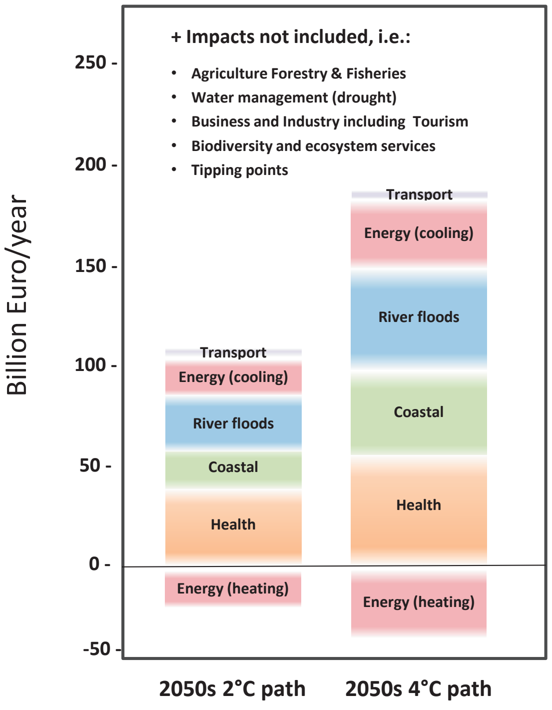
This report has undertaken a review of the current knowledge on the economic costs of climate change in Europe. It provides an update of the coverage of impacts and assesses the key gaps by sector.

The review shows that the evidence base on the costs of inaction, and the economic benefits of mitigation and adaptation are increasing, but major gaps in our knowledge remain. The synthesis also provides a number of early policy-relevant findings.

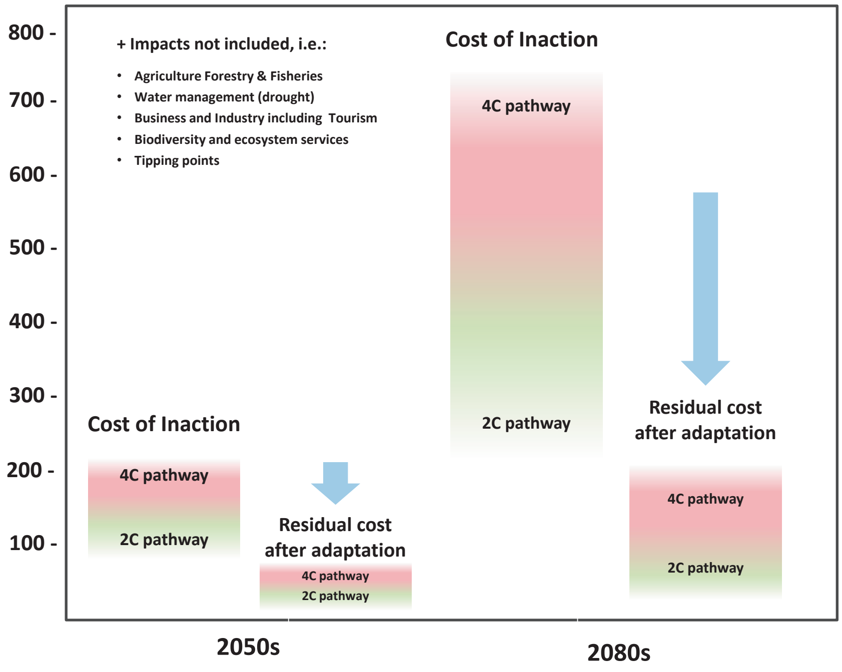
First, the review indicates that the costs of inaction will be potentially large in Europe. The figure below presents the evidence collated in this review. Details of the exact studies used are included in the appendix. It is clear that the economic costs in Europe, even by mid-century, significantly differ depending on whether the world is on a 2° or 4°C pathway. Second, the review provides evidence of the significant economic benefits to be gained from mitigation, but also from adaptation, to reduce the costs of inaction. These economic benefits rise strongly towards the end of the century.

Finally, these aggregate costs mask considerable differences in the distribution of economic costs across Europe and in individual Member States. It is important to analyse economic costs at this disaggregated level, as planned in the COACCH project, because many impacts converge on particular geographical areas.

Moving forward, the COACCH project will build on this evidence base, co-designing its research activities in direct collaboration with stakeholders to define and address key gaps and information needs and to advance the policy debate.



Indicative estimates of sectoral cost of inaction in Europe in 2050. Current prices, undiscounted. Source COACCH, 2018. See Appendix.



Indicative estimates of the cost of inaction and the benefits of mitigation and adaptation in Europe. Current prices, undiscounted. Source COACCH, 2018. See Appendix.

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Appendix

For health, values are taken from the IMPACT2C (2015b) analysis, complemented with the valuation of impacts estimated in Kendrovski et al (2017). For adaptation, the effectiveness is based on adaptation effectiveness as estimated by Chiabai et al (2018). Note that cold related mortality benefits are not included.

For coastal, values for impacts and adaptation are from the DIVA model and IMPACT2C study (Brown et al, 2015). High end scenarios for late century also draw on the RISES-AM study.

For river floods, values for impacts and adaptation are from the LISFLOOD model with estimates as presented in IMPACT2C (2015a) and ClimateCost (Rojas et al).

For energy, values for impacts are based on Mima et al (2012).

For transport, values for impacts are based on the WEATHER project (Enei et al., 2011; Przyluski, et al. 2012), the EWENT project (Nokkala et al., 2012), the PESETA II study (Ciscar et al., 2014) and the JRC study on critical infrastructure (Forzieri et al. 2018).

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COACCH
CO-DESIGNING THE ASSESSMENT OF CLIMATE CHANGE COSTS

The Economic Cost of Climate Change in Europe

Synthesis Report on COACCH Sector Results

Funded by the European Union's Horizon 2020 research and innovation programme

COACCH: CO-designing the Assessment of Climate CHange costs.

The COACCH project is co-ordinated by Fondazione Centro Euro-Mediterraneo Sui Cambiamenti Climatici (FONDAZIONE CMCC), Italy.

To find out more about the COACCH project, please visit http://www.coacch.eu/

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Introduction

Climate change will lead to economic costs. These costs, which are often known as the 'costs of inaction', provide key inputs to the policy debate on climate risks, mitigation and adaptation.

The objective of the COACCH project (**CO**-designing the **A**ssessment of **C**limate **CH**ange costs) is to produce an improved downscaled assessment of the risks and costs of climate change in Europe. The project is proactively involving stakeholders in co-design, co-production and co-dissemination, to produce research that is of direct use to end users from the research, business, investment and policy making communities

This document summarises the sector impact results from the COACCH project on the economic costs of climate change in Europe.

Definitions
The following definitions are used in COACCH

Co-design (cooperative design) is the participatory design of a research project with stakeholders (the users of the research). The aim is to jointly develop and define research questions that meet collective interests and needs.

Co-production is the participatory development and implementation of a research project with stakeholders. This is also sometimes called joint knowledge production.

Co-delivery is the participatory design and implementation for the appropriate use of the research, including the joint delivery of research outputs and exploitation of results.

Practice orientated research aims to help inform decisions and/or decision makers. It uses particpatory approaches and trans-disciplinary research. It is also sometimes known as actionable science or science policy practice.

Climate Models and Scenarios

Analysis of the future impacts and economic costs of climate change requires climate models. These in turn require inputs of future greenhouse gas (GHG) emissions, to make projections of future changes in temperature, precipitation and other variables. COACCH uses the downscaled climate projections for Europe that are available from EUROCORDEX.

As well as climate projections, analysis of future impacts and costs requires scenarios. These provide qualitative and quantitative descriptions of how socio-economic parameters may evolve in the future. These influence the economic costs that arise from climate change, for example, the population affected or the assets at risk. Most studies assess the impacts of future climate change on future socio-economic projections, as a failure to do so implies that future climate change will take place in a world similar to today

The COACCH project is producing sector estimates of the economic costs of climate change, and then feeding these into macro-economic models. This requires the use of consistent climate model projections and socio-economic scenarios. COACCH used the Representative Concentration Pathways (the RCPs), combined with the Shared Socio-economic Pathways (SSPs). These are set out in the box below.

However, this leads to a large number of potential combinations of RCP-SSPs, with too many to analyse in detail. Therefore, COACCH agreed a set of RCP-SSP combinations, focusing on a minimum core set of scenarios for use by all modelling teams. These core runs were chosen using a set of criteria, along with participatory discussion with the COACCH stakeholders on the selection.

The first criterion was the need to assess the different effects of alternative climate scenarios relative to a common socio-economic scenario. The COACCH stakeholders identified SSP2, and agreed it was useful to consider alternative climate scenarios (RCP2.6, RCP4.5 and RCP 6.0) for this scenario. Stakeholders identified SSP2-RCP4.5 and SSP2-RCP2.6 as of particular importance, and these are therefore the central scenarios of

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The Representative Concentration Pathways (RCPs)

The four RCPs span a range of possible future emission trajectories over the next century, with each corresponding to a level of total radiative forcing (W/m^2) in the year 2100. The first RCP is a deep mitigation scenario that leads to a very low forcing level of 2.6 W/m^2 (RCP2.6), only marginally higher compared to today (2.29 W/m^2, IPCC, 2013). It is a “peak-and-decline” scenario and is representative of scenarios that lead to very low greenhouse gas concentration levels. This scenario has a good chance of achieving the 2°C goal.

There are also two stabilization scenarios (RCP4.5 and RCP6). RCP4.5 is a medium-low emission scenario in which forcing is stabilised by 2100. It is similar to the A1B scenario from the SRES. Even in this scenario, annual emissions (of CO_2) will need to sharply reduce in the second half of the century, which will require significant climate policy (mitigation). Finally, there is one rising (non-stabilisation) scenario (RCP8.5), representative of a non-climate policy scenario, in which GHGs carry on increasing over the century. Leading to very high concentrations by 2100. Note that achieving RCP4.5 or below always requires mitigation, but more is required under SSP3 and SSP5. There are also new RCP 2.0 pathways being constructed for a 1.5°C pathway.

The Shared Socio-economic Pathways (SSPs)

The Shared Socio-economic Pathways (SSPs) provides a new set of socio-economic data for alternative future pathways. They include differing estimates of future population and human resources, economic development, human development, technology, lifestyles, environmental and natural resources and policies and institutions. Note that the SSPs include a quantitative and qualitative component.

Five alternative future SSPs are provided, each with a unique set of socio-economic data and assumptions. SSP2 is the central, Business As Usual (BAU) scenario, as it relies on the extrapolation of current trends. The SSPs are presented along the dimensions of challenges to mitigation and adaptation. For example, in a world in which economic growth is high, there are sufficient resources to adapt, but the challenges in mitigation are high.

SSP1	Sustainability	Adaptation: low	Mitigation: low
SSP2	Middle of the Road	Adaptation: moderate	Mitigation: moderate
SSP3	Regional Rivalry	Adaptation: high	Mitigation: high
SSP4	Inequality	Adaptation: high	Mitigation: low
SSP5	Fossil-fuel Development	Adaptation: low	Mitigation: high

Finally, to analyze the effect of mitigation strategies (for specified forcing levels), different **Shared climate Policy Assumptions (SPAs)** have been identified, which use carbon taxes to achieve the required emission levels, but consider different tax regimes (global versus rich countries, different pricing of land use emissions, etc.).

the COACCH project. For these scenarios, a more detailed analysis of climate model uncertainty and different adaptation assumptions are undertaken.

However, both stakeholders and researchers considered it was important to explore extreme scenario combinations. For this reason, the choice of SSP5-RCP8.5 was agreed to analyze the important aspect of impacts under high-climate change futures and SSP1-RCP2.6 under low climate change futures.

The second criterion was the need to unpick the effects of different socio-economic effects (i.e. SSPs). For this reason, a single climate projection (RCP4.5) was selected for analysis with SSP1, SSP2 (core), SSP3 and SSP5. This allows the project to separate out the relative importance of

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Table 1: Selected scenario combinations to be used in the COACCH project

	SSP1	SSP2	SSP3	SSP4	SSP5
	(Green Growth)	(Middle of the road)	(Regional rivalry)	(Inequality)	(Fossil fuel development)
RCP8.5					🟡
RCP6.0		🟡			
RCP4.5	🟡	🟢 🟡 🔴 🔵	🟡		🟡
RCP2.6	🟡	🟢 🟡 🔴 🔵	🟡		

🟢 = "low signal" climate model; 🟡 = "average" climate model; 🔴 = "high signal" climate model;
🔵 = fixed adaptation, "average" climate model

* The "low signal" and "high signal" climate model refers to, respectively, choosing a model which leads to relatively low/high temperature change and/or to low/high precipitation changes.

climate versus the socio-economic signal. Finally, the project included SSP3-RCP2.6 and SSP3-RCP4.5, to provide inter-comparison data with the central scenario combinations. The final selection of RCP-SSP combinations are summarized in the Table.

Climate Projections for Europe

The COACCH project uses existing climate projections, but to provide background context, the findings are summarised in this section. The latest climate model projections find that Europe will warm more than the global average, i.e. Europe will experience more than 2°C of warming (relative to pre-industrial levels) even if the Paris goal is achieved in terms of emissions. However, the patterns of climate change differ across Europe.

At 2°C of global mean warming, the Iberian Peninsula and other parts of the Mediterranean could experience 3°C of warming in summer, and Scandinavia and the Baltic 4°C of warming in winter. These areas will also reach 2°C of local warming much earlier in time i.e. in the next couple of decades. These trends are exacerbated under higher warming scenarios.

There are also projected increases in extreme events in Europe even for 2°C of global change, which will cause more frequent and severe impacts. This includes increases in daily maximum temperature, extremely hot days and heatwaves over much of Southern and South-Eastern Europe, although relative to current temperatures, there will also be large increases in heat extremes in North-East Europe.

There are also robust model findings of increases in heavy precipitation in Europe, in both summer and winter, with (ensemble mean) intensity increasing by +5% to 15% (and in some areas, even more), even under the 2°C scenario. The projected increase in heavy precipitation is expected also over regions experiencing a reduction of the average precipitation (such as southern Europe). These increases drive potential increases in flood risk.

The change in average precipitation from different climate simulations varies considerably by model. On average, increases of +10-15% in winter precipitation are projected for Central and Northern Europe for 2°C, and increases in summer precipitation for Northern Europe. At the same time, decreases in summer precipitation, of the order of –10-20%, are projected for Central and Southern Europe.

This is of high policy relevance: even if the 2°C goal is achieved, Europe will still experience large potential impacts.

It is highlighted that these results involve 'uncertainty'. One unknown factor affecting future climate is the GHG emission path (the

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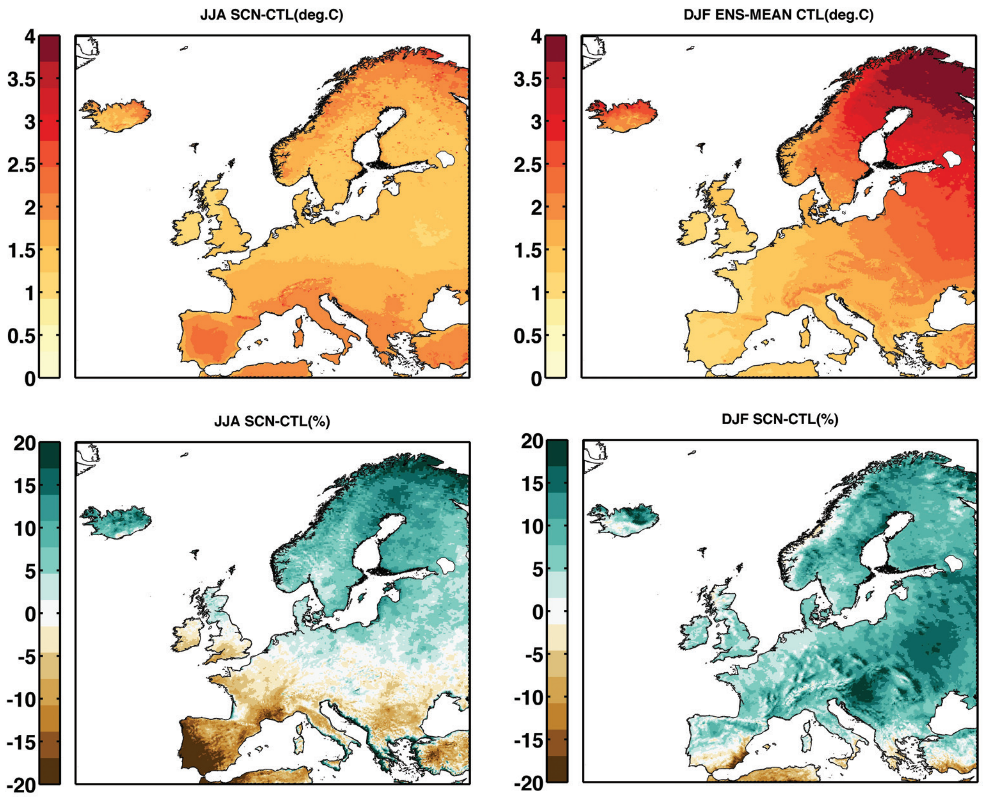

The increase in seasonal temperature (from 1971–2000) (Top) and Seasonal Precipitation (Bottom) across Europe at 2°C of global average warming. Left (summer). Right (winter).

Average RCM simulated precipitation between the reference period (1971–2000) and period corresponding to global temperature difference of 2°C. Source: Stefan Sobolowski et al, 2014. IMPACT2C project.

future RCP), though this can be considered with multiple scenarios (see Table 1 above). Another factor is that climate models do not all give the same results, though this can be considered by using different models. It is essential to recognise this uncertainty, not to ignore it or use it as a reason for inaction. This is captured by the consideration of different climate models for the core scenarios, see Table 1.

New COACH Sector Economic Cost Estimates

The COACCH project has produced new sector estimates of the economic costs of climate change. These are presented in this section, reported as the monetised impacts in terms of social welfare. This captures the costs and benefits to society, i.e. market and non-market impacts. These estimates are presented in terms of current prices (Euros) for future time periods, without adjustment or discounting. This facilitates direct comparison, over time and between sectors. Where possible, results are reported as the combined impacts of future climate and socio-economic change together, along with a commentary on the importance of climate versus socio-economics in the estimates. Where possible, analysis of the costs and benefits of adaptation has been included.

Coastal flooding

Introduction. 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.

The economic costs of coastal impacts – and adaptation – are among most comprehensively covered areas. Methods for assessing large scale coastal flood risks have developed and been widely applied, at multiple scales. COACCH 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.

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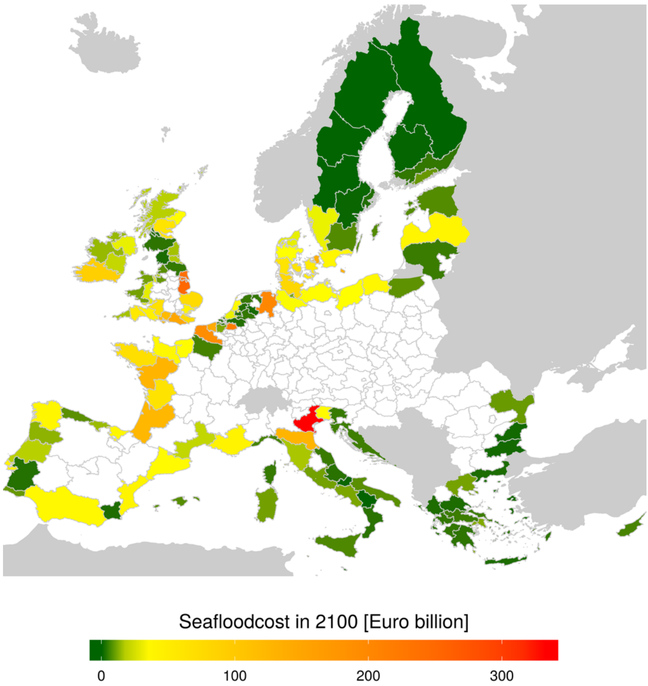
COACCH Economic Cost Estimates.
COACCH has assessed the potential impacts and economic costs of sea-level rise in Europe, and the costs and benefits of adaptation. The analysis has considered future climate and socio-economic change. As floods are probabilistic events, the results are presented as expected annual damage (EAD) costs (undiscounted).



Seaflood cost map

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 such as erosion, leads to high economic costs in the case of no adaptation, shown in the table over the page. The expected damage costs in Europe (EU28) from the combination of climate and socio-economic change are estimated at €135 billion/year to €145 billion/year for the 2050s (mid estimates for RCP2.6 and RCP4.5 respectively), rising to €450 billion/year to €650 billion/year by the 2080s for the same scenarios. These costs include direct impacts. Additional unquantified costs will occur due to ecosystem losses and possible knock-on effects of damage on other sectors.

There are major differences in the damage costs borne by different Member States, with strong distributional patterns across Europe, as shown in the map of coastal damages. 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.

These costs are projected to rise rapidly by the late century, notably for the higher emission RCP6.0 and especially for the RCP8.5 scenario. The latter shows a disproportionate increase in costs in the second half of the century. This highlights the benefits of mitigation strategies, as shown by the low damage costs in the 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.

The new COACCH numbers are higher than earlier studies, especially for the late century, high-end scenarios. This reflects the higher increases in sea-level rise projected in recent assessments, but also the influence of socio-economic drivers (especially in the SSP5 scenario).

It is stressed that there is a wide range of uncertainty around the central estimates,

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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

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

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 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.

reflecting the underlying uncertainty in global temperatures and the sea- level response, as well as the role of ice sheet melt. Analysis of extreme sea-level rise, i.e. of projections estimating over 1.5m by 2100, are presented separately in the COACCH tipping points briefing note.

COACCH Adaptation Economic Estimates. The DIVA model has also been used to look at coastal adaptation in Europe 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 in the EU28 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. 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 (and costs) 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.

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 to acceptable level of risk protection or based on economic efficiency. Furthermore, there is a need to recognise and work with uncertainty. This requires an iterative and flexible approach for adaptation planning, noting that this needs to be positioned within a broader integrated coastal-zone management policy framework.

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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 Flooding

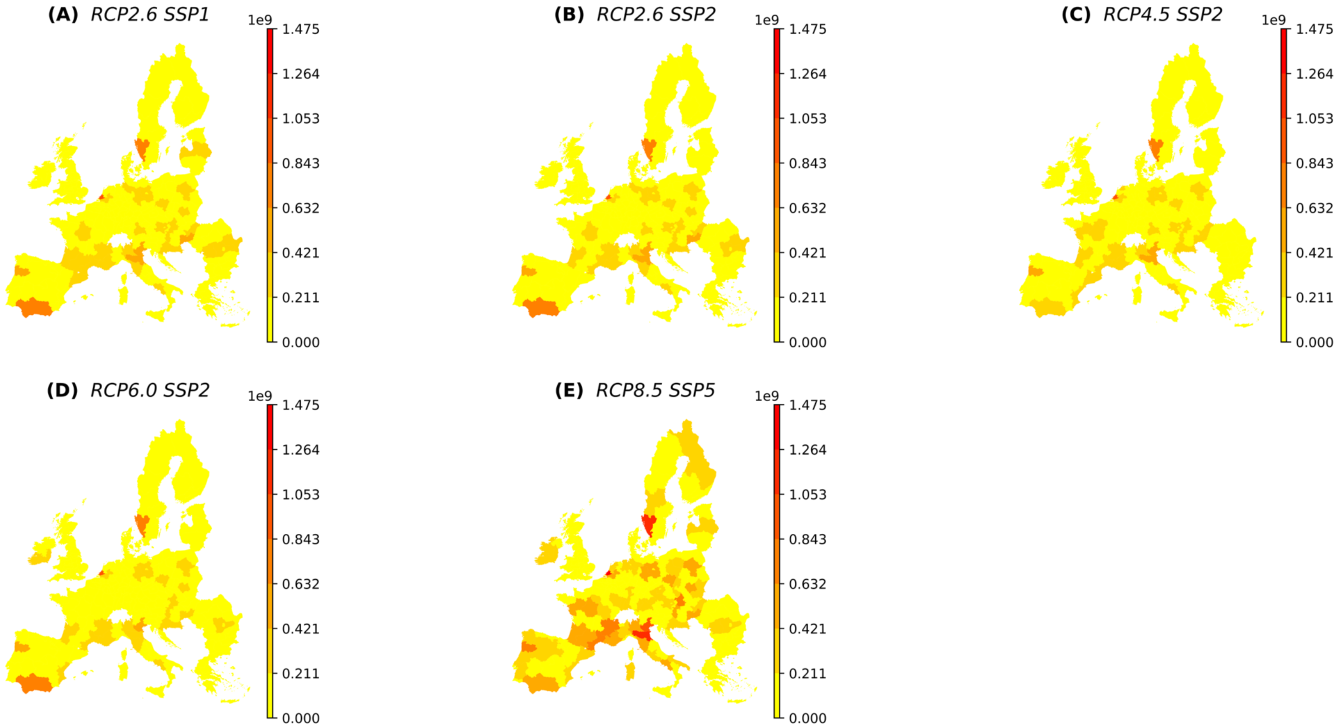
Introduction. River floods are one of the most important weather-related loss events in Europe and have large economic impacts, as reported in recent severe flooding events. Climate change will intensify the hydrological cycle and increase the magnitude and frequency of intense precipitation events in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

COACCH Economic Cost Estimates. The COACCH project has used the GLOFRIS model to assess the potential direct impacts of climate change on floods in Europe. As floods are probabilistic events, the results are presented as expected annual damage (EAD) costs (undiscounted).
The annual expected damage costs in Europe

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 or costs relative to the baseline period for the EU28, from the combination of climate and socio-economic change, and are presented as undiscounted values in future years in current prices.



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

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European River Flood Damage Costs (EAD) for Various RCP scenarios (WITH Optimal 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 or costs 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.

(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).

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

The results also show that 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.

COACCH Adaptation Estimates. 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, which are estimated at hundreds of billions of Euro in Europe (cumulatively, over time).

As with the 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, and there is a need to recognise and work with uncertainty, as well as to progress detailed, local scale assessments.

Transport

Introduction. 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 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.

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European Flood Impacts on Transport (Direct Impacts only) in Europe (no adaptation).

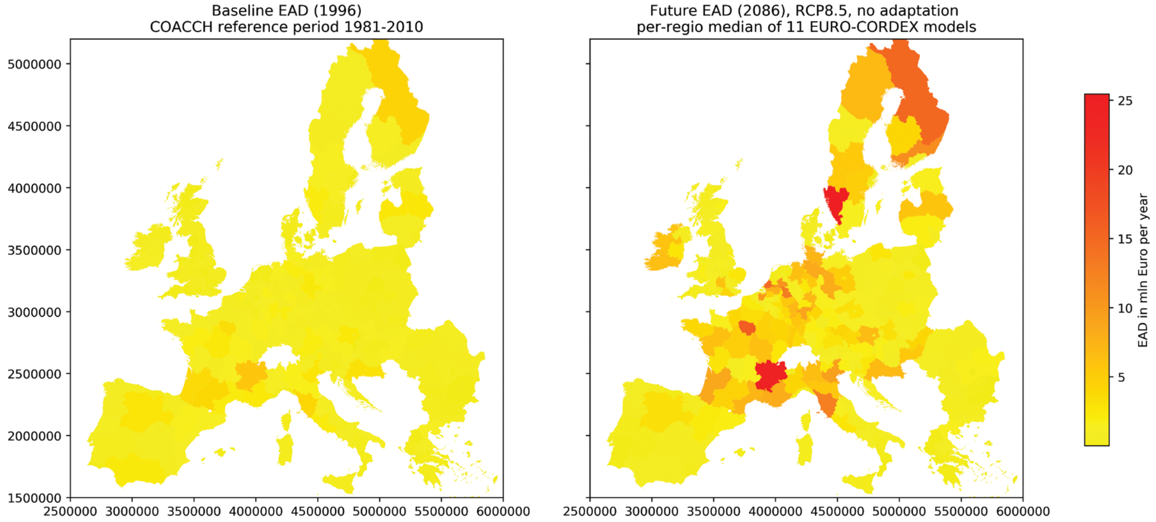
	RCP4.5-SSP2	RCP8.5-SSP5
2050s / mid century	€954 M/yr	€1147 M/yr
2080s /end century	€1469 M/yr	€2286 M/yr

Values are presented as additional impacts 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.

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 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.


Baseline EAD (1996)
COACCH reference period 1981-2010

Future EAD (2086), RCP8.5, no adaptation
per-regio median of 11 EURO-CORDEX models

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

Economic cost estimates. 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. 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.

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

When river flood adaptation is included, as analysed in the earlier river flood section,

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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.

Business, Services and Industry

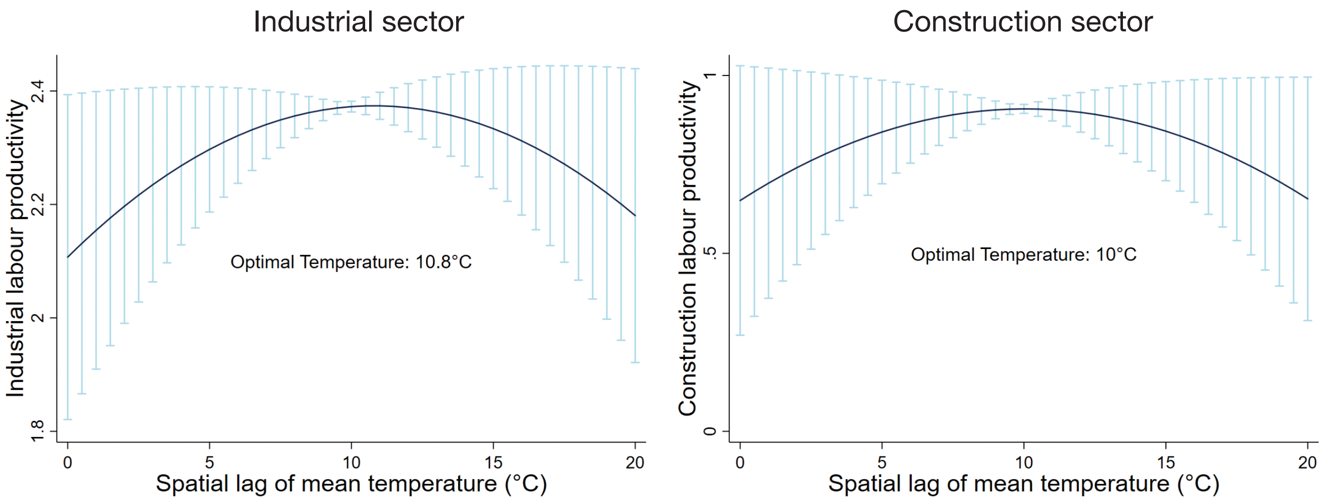
Introduction. Climate change impacts such as floods, high temperatures, and water availability, will all impact business and industry. The balance of risks will vary with sub-sectors and locations, and sites and operations will be affected differently. Risks also extend along supply chains, with impacts 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.

COACCH Economic Cost Estimates. 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.

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 by 4.3% and



The relationship between mean temperature and productivity at the NUTS-2 level, including 95% confidence interval (light blue spikes).

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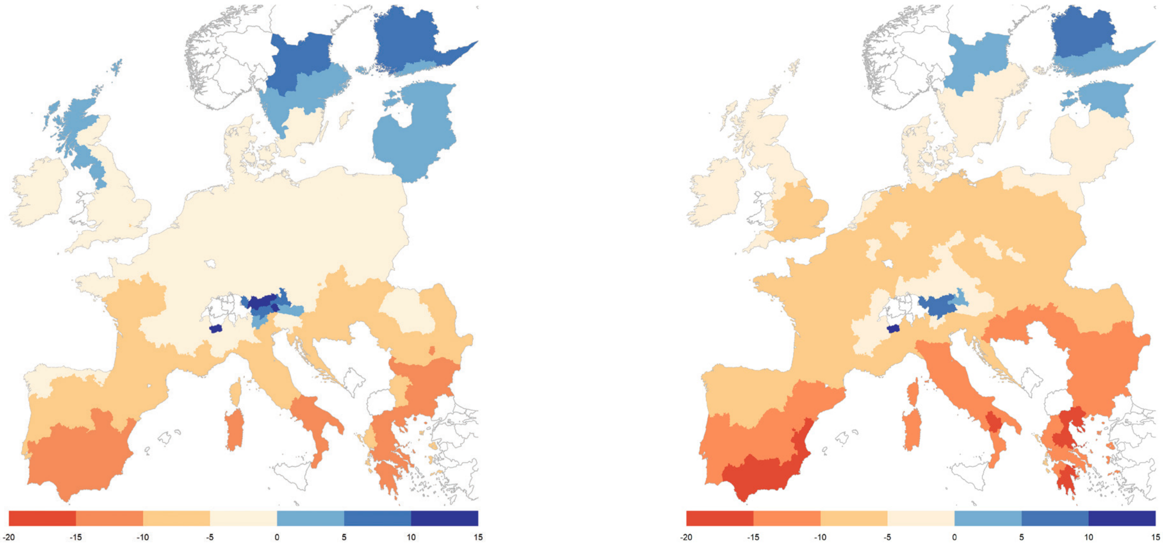

Future impact under RCP8.5 on industrial (left-panel) and construction productivity (right-panel) by 2070. The impacts are computed using the Delta method and a reference period of 1985–2005.

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 above. 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.

The analysis of current **tourism** and climate data found that average and maximum temperature correlates with tourist flows (arrivals, nights spent) positively up to a temperature optimum but declines above this, with very sharp decreases at high values. However, the threshold levels varies with region. 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. The project is now using these relationships to look at future climate change.

Finally, the analysis has determined the potential impacts of climate change on the interplay of supply chains shocks and a sector's export value. The findings are that all countries' sectoral exports are negatively affected by climate change, and it could additionally reduce a sector's export value by up to 16 percent. However, these findings vary strongly between countries as well as sectors. The largest impacts occur in the tropics and sub-tropics, due to the stronger projected climate impacts, which are then transmitted over interregional supply chain connections. The findings suggest that

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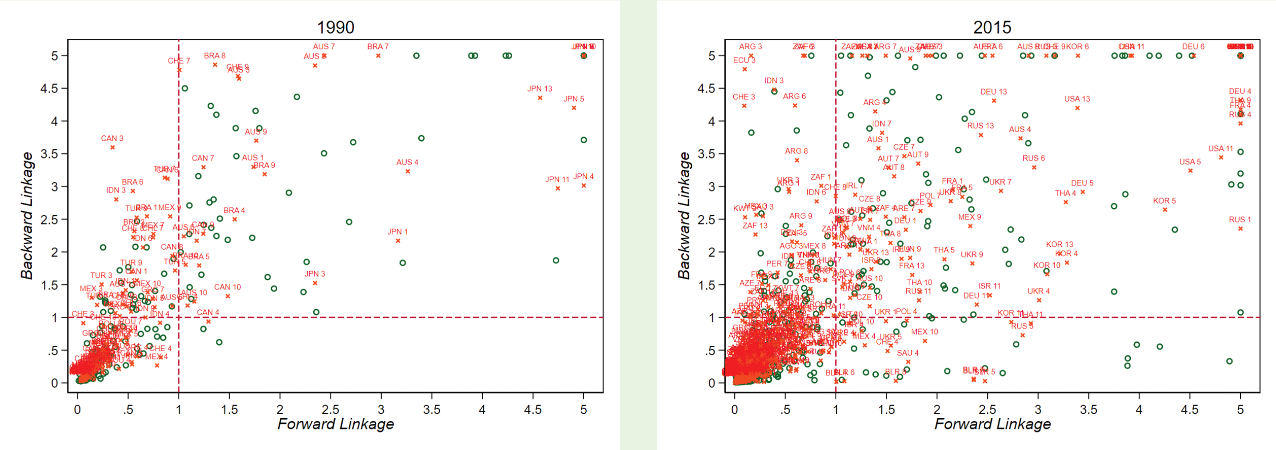
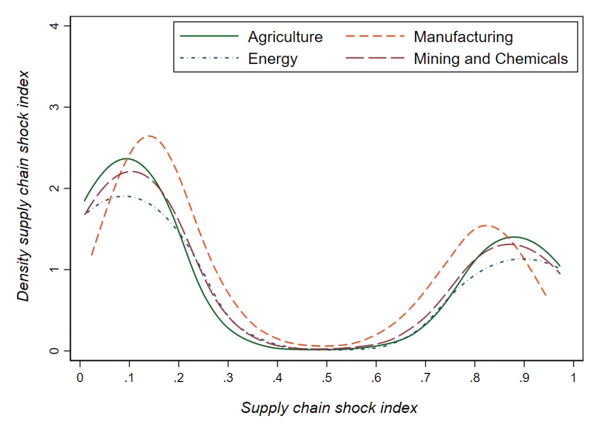
Sectoral Exports, Supply Chain Shocks and Climate Change

The production of a final good in a country is based on many input-output interlinkages domestically as well as internationally. This means that disturbances in one country can propagate along the supply chain, leading indirectly to a change in other countries' macroeconomic outcomes. The COACCH project has undertaken new analysis on the transmission of climate shocks in international supply chains. This assessed input-output connectivity between sectors and countries, along with data on extreme weather. The findings show the increase in international supply chains over time (from 1990 to 2015), and that sectors with strong supply chain interlinkages are regularly hit by natural disasters (sectors to the upper right of the figure and marked with red).



Sectoral forward and backward linkages and disaster shocks

The analysis then assessed the distribution of received supply chain shocks for regions and sectors. This leads to some interesting findings. The EU – due to the single market and stronger export orientation – receives more supply chains shocks from abroad than the USA. The effects are largest for manufacturing and agriculture.



Distribution of supply chain shock index by sector in Europe

The analysis looked at the impact of supply chain shocks on a sector's export performance. It found that productivity shocks transmitted over the supply chain significantly reduce a sector's export performance: on average a one standard deviation increase in supply chain shocks reduces a sector's export value by around 11%.

Finally, the analysis assessed the potential impacts of climate change on the interplay of supply chains shocks and a sector's export value. The findings are that all countries' sectoral exports are negatively affected by climate change, and it could reduce a sector's export value by up to 16 percent. However, these impacts vary strongly between countries and sectors. The largest impacts occur in the tropics and sub-tropics, due to the stronger projected climate impacts, which are then transmitted over interregional supply chain connections. The findings suggest that policy makers as well as companies need to the take account of the rising risk of supply chain disruptions due to climate change. Potential adaptation measures could include a geographical diversification in global supply chain networks, intensification in the use of storage facilities or firm-level insurance against risks.

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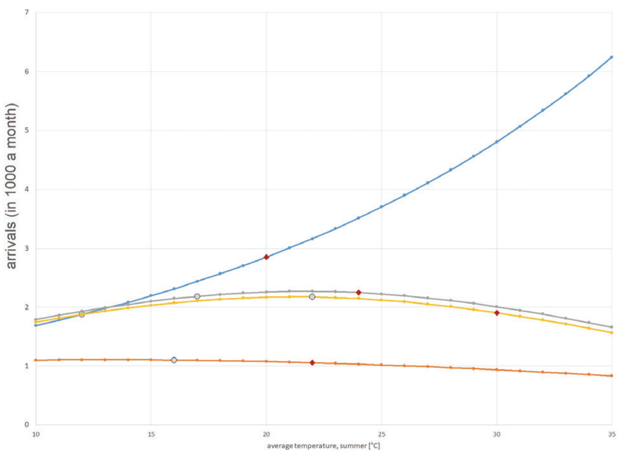
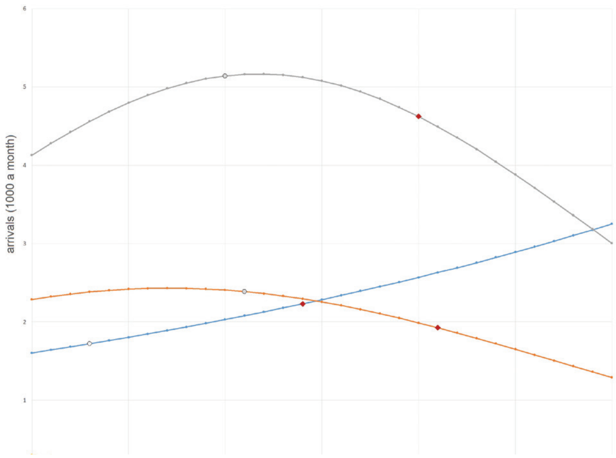


Effect of mean temperature on tourists arrivals



Effect of maximum temperature on tourists arrivals

policy makers as well as companies need to the take account of the rising risk of supply chain disruptions due to climate change. Potential adaptation measures could be, for example, a geographical diversification in global supply chain networks, intensification in the use of storage facilities or firm-level insurance against supply chain risks.

Energy

Introduction. 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 Economic Cost Estimates.
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 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.

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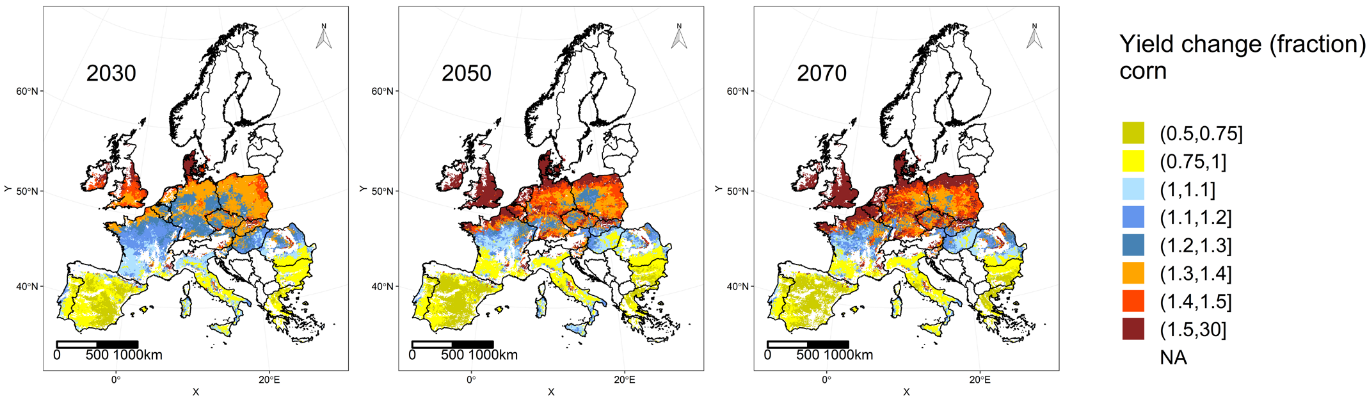
Agriculture

Introduction. 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 prevalence of pests and diseases. These will affect crop yields and, in turn, agricultural production, consumption, prices, trade and decision-making on land-use.

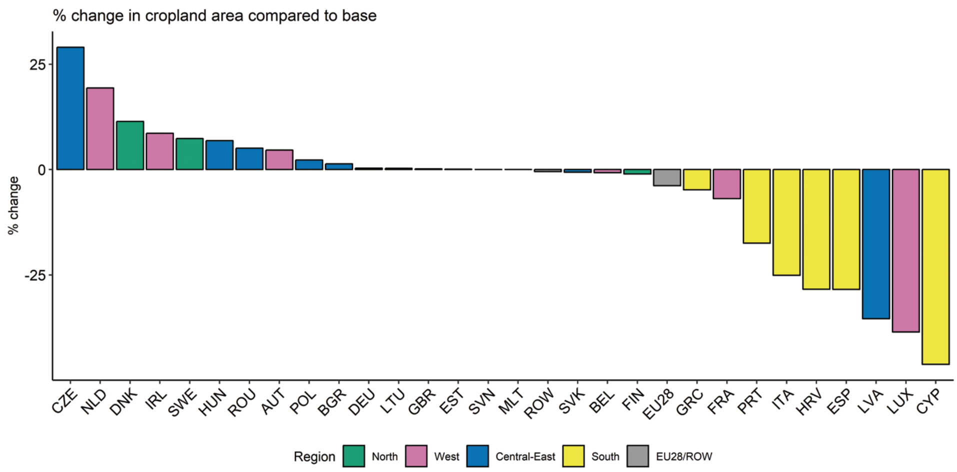
COACCH has developed new estimates, using a suite of models and assumptions to quantify the costs of climate change. This uses a range of GCMs, three crop models (EPIC, GEPIC and LPJmL), and two bio-economic models (MAgPIE and GLOBIOM) covering the agricultural, forestry and fisheries sector. The impact of factors that impact uncertainty, such as CO_2 fertilization, have been quantified.

COACCH Economic Cost Estimates. The GLOBIOM model was used to estimate the impact of climate change on EU-28 production, area, and yield, looking at individual crops and broad agricultural categories. The results produced different estimates to previous studies.

In all scenarios (low, medium and high warming scenarios), when CO_2 fertilization is included, crop productivity increases on average in Europe, but shows large differences between crop types, as well as spatial differences within Europe. The biophysical crop model EPIC shows that large negative impacts are expected especially for corn in Southern Europe, whereas cereals such as wheat are more resilient against



Fraction of yield change due to climate for corn productivity under RCP4.5, HadGEM-ES.



Percentage change in cropland by country under RCP4.5, HadGEM-ES in 2050.

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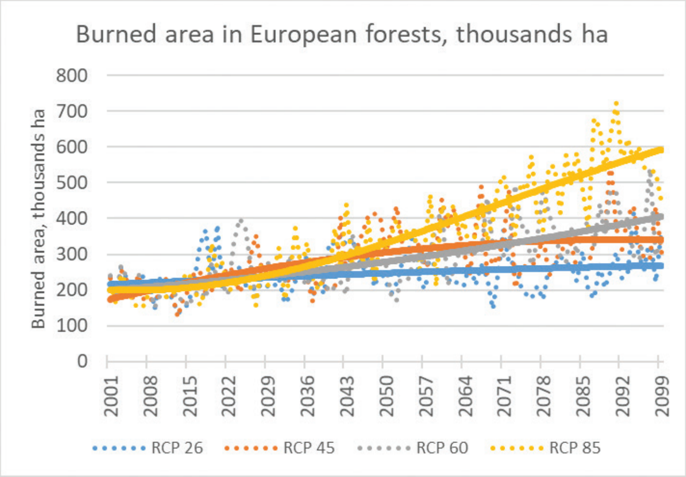
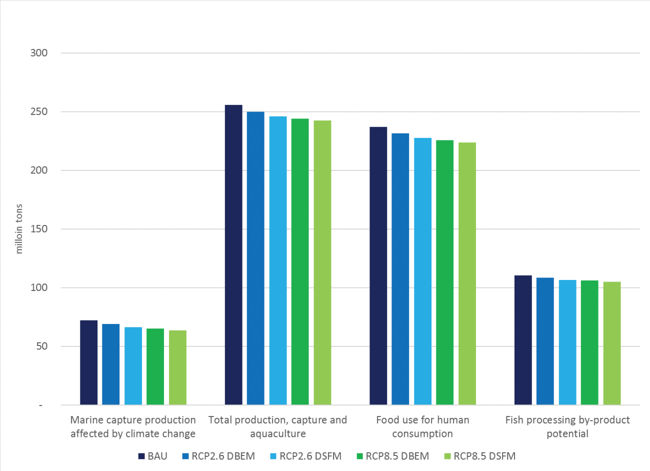


Projected burned areas in European forests.



Model projections of the impacts of climate change on marine capture fisheries.

climate change. This is due to their response to CO_2 concentrations.

The bio-economic model GLOBIOM shows that the large losses for maize production under different RCP combinations lead to increases in area cultivated with the same crop; however, not enough to compensate for the loss in production. Small yield gains in cereals and oil seeds on the other hand lead to small area reductions in for these crops. Furthermore, the change in relative competitiveness under climate change induces a reallocation of agricultural practices between European countries; cropland area especially reduces in the South of Europe, whereas it increases in the North, West and Central-Eastern countries.

Highest negative impacts on both crop yields and the agricultural sector in general, are found under a high emission scenario (RCP8.5) whenCO_2 fertilisation is not considered. GLOBIOM estimates 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. 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.

Forestry and Fisheries

Introduction. Forestry is a sector with long life-times, and thus 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. 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 human fishing activities are the dominant factor for commercial fisheries, climate change will add additional pressure.

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. The biophysical forest model G4M estimates that increased temperature and decreased precipitation cause a reduction in the biomass and growth rate of forests in Southern Europe, especially towards 2070 under RCP8.5. In the short-term, smaller gains on biomass growth can be expected mostly in Northern Europe.

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For forestry, the Wildfire Climate Impacts and Adaptation Model (FLAM) is used to capture impacts of climate, population, and fuel availability on burned areas along with IIASA's global forestry model G4M. For fisheries, COACCH uses the GLOBIOM model to look at changes in annual catch and the redistribution of stocks or catch potential.

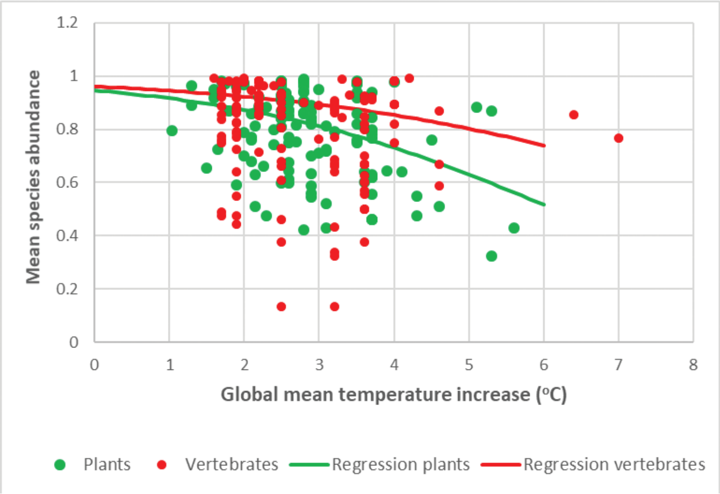
COACCH Economic Cost Estimates. Under RCP8.5 and without CO_2 fertilization, GLOBIOM estimates that the costs of climate change for forest production, related to the loss of biomass, amount to 62 million Euros in 2050 and 11.2 billion Euros in 2070. In addition, forest fires currently affect more than half a million hectares each year in Europe, with estimated annual economic damages of €1.5 billion (San-Miguel-Ayanz et al, 2010). The new analysis in COACCH estimates that the potential burned area in Europe will increase significantly in Europe (see below), especially under the RCP8.5 scenario. The areas (in ha) are estimated to be Portugal, Spain, South of France and Greece. The COACCH project has also looked at potential adaptation options (prescribed burning, improved fire suppression), which have been found to significantly reduce the annual burned areas.

For capture fisheries, 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 are able to partly mitigate negative changes: this means that fisheries near the equator are affected more negatively, while some higher latitudes may gain. Nonetheless, 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. GLOBIOM estimates that for the EU28, a reduction of between 0.7 and 1.2 million tones is estimated for RCP2.6 and between 0.8 and 1.0 million tons for RCP8.5 (in 2050). It is noted that these estimates do not take into account additional impacts from marine extremes and ocean acidification.

Biodiversity and Ecosystem Services

Introduction. Climate change poses very large risks to terrestrial, aquatic and marine biodiversity and the ecosystem services they provide (provisioning, regulating, cultural and supporting services). It will shift geographic ranges, seasonal activities, migration patterns, reproduction, growth, abundance and species interactions, and will increase the rate of species extinction, especially in the second half of the 21st century (Settele et al., 2014). As well as terrestrial ecosystems, there are potentially large impacts on marine ecosystems, including from ocean acidification, ocean warming and sea-level rise, as well as impacts on freshwater ecosystems (rivers and lakes). However, this is one of the most challenging areas for economic cost analysis.

COACCH Economic Cost Estimates. COACCH is developng new analsis using a suite of models. This includes GLOBIO, a scenario-based gridded global model for biodiversity. This estimates the Mean Species Abundance – an indicator of biodiversity. Early results indicate that while natural vegetation cover remains broadly constant in Europe under climate change, there are projected to be movements of specific biomes. There is also projected net decline, on average, in MSA under climate change scenarios – the decline being greater under RCP8.5 than RCP2.6. These early results are being used to look at potential economic impacts, including ecosystem services.



Mean Species Abundance – pressure curve resulting from envelope model studies for both plants and vertebrates

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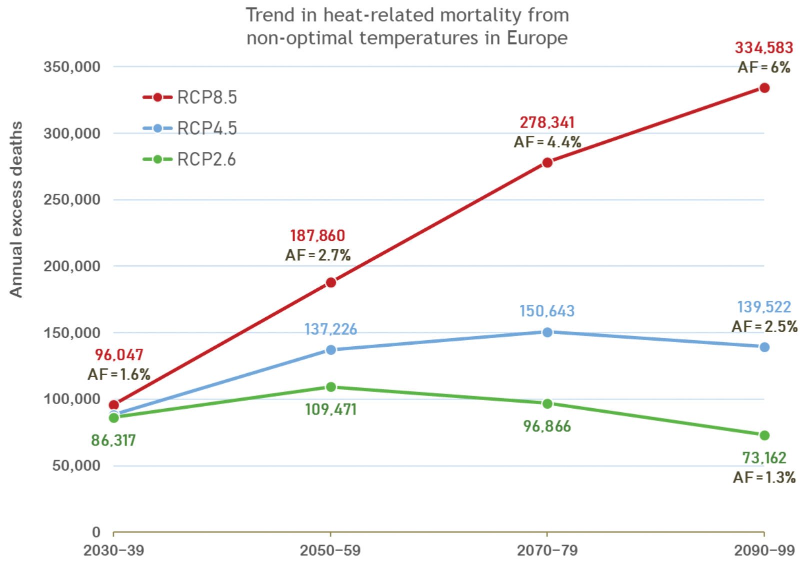
Health

Introduction. There are a number of health impacts from climate change. These include direct impacts, such as heat-related mortality, deaths and injuries from flooding, etc., but also indirect 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 Economic Cost Estimates. COACCH has assessed the impact of climate change on heat-related mortality. 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. These estimates are higher than previous estimates, reflecting updated climate projections and the inclusion of excess heat. The highest number of fatalities are projected in southern and central 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.



Trend in annual excess deaths attributable to heat (moderate and excessive).

Economic Costs of European Heat-wave-related Health Impacts for Various RCP scenarios (no adaptation or acclimatisation, VSL approach).

	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.

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Distribution across Europe for RCP4.5, decade 2090-99

These new monetary values have then been applied to the impacts estimated in the figure above. However, they have only been applied to the mortality associated with excess heat/heatwaves, as this is the specific context in which the WTP values were derived. To do this the analysis assumes that on average, extreme heat is responsible for approximately 45% of total heat-related fatalities: this proportion was based on a detailed country-specific analysis in the COACCH project.

These results indicate that these non-market impacts could be very large, in fact, they are larger than the other sectors reported. This also means there are high economic benefits from mitigation policy, with very large annual economic benefits in moving from high warming (RCP8.5) to moderate (RCP4.5) and also to ambitious mitigation scenarios (RCP2.6).

However, there are a number of caveats with these estimates. First the physical impacts calculated do not take account of physiological acclimatisation to heat over time. Accounting for this would likely 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 many heat-wave related deaths may be short. Other studies have accounted for this by adjusting VSL estimates, for example deriving and using a Value of a Life Year Lost, combined with estimates of average life expectancy losses. The use of this type of adjusted values leads to significantly lower total economic costs from heat events, lowering the values in the table by over an order of magnitude.

The COACCH analysis has also looked at additional impacts from climate change on tick-borne diseases in Europe (Tick-borne encephalitis and Lyme disease). These ticks are sensitive to temperature, and climate change will alter their range and prevalence, including

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potential expansion into new areas. The COACCH project has undertaken a willingness to pay study, using stated preference surveys in the Czech Republic, Slovakia, and Austria, to derive new economic costs for tick-borne diseases, as well as public references for programmes to reduce the spread of tick-borne diseases.

COACCH Adaptation Economic Estimates. The COACCH study has also considered the potential benefits of adaptation, specifically heat alert systems, in reducing the excess heat related fatalities reported above. These systems are already in operation in many countries, and will have potentially greater benefits under climate change, however, they will also involve higher resource costs to operate, as they are triggered more with rising temperatures. COACCH has looked at these relative costs and benefits, assessing a case study assuming national systems operating across Europe (though it is stressed that such schemes are very site- and context-specific).

The benefit-cost ratios for implementing heat warming schemes across Europe for future climate change scenarios, using both the VSL and VOLY metrics. When the VSL metric is used, the benefit-cost ratio is very large across all European regions, under all future scenarios. When the VOLY metric is applied, the benefit to cost ratio is above one for Northern and Central Europe, but potentially below one for Southern Europe. This reflects the fact that the resource costs of responding to heat alerts in the South – from events being triggered so frequently – increase faster than benefits. This highlights that in these areas, heat alert systems on their own are unlikely to be the most efficient and effective measures, and a broader portfolios of complementary adaptation options is likely to be needed.

Macroeconomics, growth and competitiveness

Introduction. A number of studies consider the wider economic costs of climate change in Europe and globally. These can investigate the relationship between climate change and the economic performance of countries, most commonly represented by indicators of competitiveness, GDP and, in broader terms, growth. This is a step beyond the aggregation of costs at the sectoral level, as it aims to identify the interactions across different impacts, and the economic reaction and transmission channels (including market-driven adaptation). It also can assess how these interactions affect the overall capacity of country economies to produce goods, services and ultimately “welfare”.

COACCH Activities. COACCH is assessing the macro-economic effects of climate change by feeding sector results into economy-wide simulation models, notably computable general equilibrium (CGE) models. This has the advantage of capturing the whole economy (sectors, domestic and international interlinkages) and can analyse impacts on national production, welfare and GDP.

COACCH is also running a number of global and continental economic estimates provided by “hard-linked” integrated assessment models (IAMs). These provide a self-consistent integrated analysis of emissions, climate change, impacts and economic effects, including both market and non-market impacts. They report aggregate economic impacts as a % of GDP, through simplified and compact damage functions, rather than undertaking full macro-economic analysis.

The sector results reported in earlier sectors have been used to assess the macro-economic effects of climate change in Europe. This is reported in a separate policy brief (Number 4). This has also considered whether climate change might actually affect the drivers of growth (and growth rates), not just levels of outputs. Alongside this, COACCH is looking at the effects of these economic impacts on public budgets in Europe. This recognises that changing trends, as well as increasing climate shocks, may have implications for public finances.

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