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ACCREU Assessing Climate Change Risk in EUrope

Assessing Climate Change Risk in Europe

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Introduction

Research framework and objectives

EUROCORDEX[1] projections confirm 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 (Tröltzsch et al., 2018). The impacts of climate change are already perceivable in Europe, and, with high confidence, they will intensify in the 21st century given a faster warming of the European Continent with respect to the global average (Bednar-Friedl et al. 2022). According to (Szewczyk et al. 2020), a scenario of +3°C by the end of the century will cost the EU 175 billion €/year (1.38% of GDP) in 2050, whereas curbing temperature increase below 2°C will halve the figure.

Major impacts have been already observed in the four areas that will probably face the greatest risk in the future: i) heat-related human morbidity and mortality, as well as heat impacts on marine and terrestrial ecosystems; ii) losses in crop production; iii) water scarcity; iv) river and coastal flooding, including impacts on cultural heritage and long-living infrastructure. While some results suggest that gradual warming may benefit the EU (Shleypen et al., 2022, Bosello et al., 2020), this benefit may result in a net loss if extreme events worsen. Furthermore, the impacts are different at the national and regional levels and differ across economic sectors, which supports the need for further studies at the subnational and sectoral dimensions. Even in the most optimistic scenario of 1.5°C warming, major losses are expected for the agriculture and services sectors, being these losses lower if compared with a 2.0°C scenario, suggesting that even 0.5°C warming can make a difference for the EU economy (Shleypen et al., 2022).

Characterising the **regional heterogeneity** of climate risk in the EU is crucial to provide policymakers useful information for directing support towards the most vulnerable areas of EU member states. According to Bednar-Friedl et al. 2022, economic losses and damages are analysed for European economies from multiple Key Risks. Damages are overall projected to increase and potentially quadruple at +3°C compared with +1.5°C scenarios. While losses are highest in Southern Europe for both +1.5°C and +3°C, the projected economic damages and losses also increase significantly in Western and Central Europe (accounting for 40% of total losses in EU-28 at +3°C) and in Northern Europe (almost 10% of total losses at +3°C). Bosello et al. 2020 analyse climate change impacts in the EU, reporting a median GDP loss of 2.2% between 2020 and 2070, while one fourth of EU regions could experience GDP losses larger than 5% within the same period, as for South and East EU regions (around 5%), with Latvia experiencing the highest costs, above 10%. Out of nine sources of climate change impacts considered, the main drivers of macroeconomic impacts are sea-level rise, riverine floods, and crop yield changes. The study also stresses that those estimates do not consider important **non-market impacts** such as **impacts on health, biodiversity and ecosystem services** which would increase overall costs.

Another important aspect to consider when assessing climate change risks is the **interactions among multiple hazards**, since new evidence shows that interactions across numerous sectoral, regional, and response-option boundaries strongly influence some of the most severe climate change effects (Simpson et al. 2021). Addressing hazards separately can lead to inaccurate response-plans that miss the complexity of climate change risks since adverse impacts are usually caused by multiple hazards that can then lead to **cascading effects**. Compound and cascading natural hazards usually cause more severe impacts than any of the single hazard events alone (Sutanto et al., 2019). For example, crop failure is commonly induced by the occurrence of multiple and combined anomalous meteorological drivers (Goulart et al., 2021). Different physical climate storylines are thus needed to explore complex impact transmission pathways and possible alternative event cascades under future climate conditions (Ciullo et al., 2021).

Focusing on the present European framework **ACCREU** is expected to advance the knowledge of climate change impacts and offer viable policy solutions guided by the needs of users. In this, a comprehensive, integrated, updated and co-designed assessment of climate risks will be asessed under different climate and socio-economic scenarios. The assessment of costs, benefits, effectiveness, limits, and feasibility of **adaptation** against different impact types and scales will be improved to fully integrate mitigation, adaptation, and residual climate damages into new research and decision-making space.

[1] Euro Cordex EURO-CORDEX Data

The objective of this report is to provide a coherent and comprehensive framework of the main research questions that ACCREU will address, underlying key knowledge gaps and modelling improvements needed.

In the first part, key sectors and relevant sources of climate change impacts will be analysed, with the aim of providing a framework of the most recent existing knowledge and major gaps at the European level.

In the second part of this report an analysis of the most recent socio economic scenario framework will be assessed. The future socioeconomic scenarios to date considered most plausible will be evaluated in order to provide a coherent and consistent scenario framework from which to structure future research.

PART I: STOCKTAKING AND GAP ANALYSIS

The core objective of ACCREU is to cover the existing knowledge gaps, with the ambition to advance the current understanding of climate change impacts on Europe and offering viable policy solutions. On the basis of the most recent research and latest climate information available, ACCREU will improve the assessment of those impact categories most relevant for EU, investigating transmission channels that the previous literature largely neglected as fiscal and financial effects, supply chain, non-market impacts of climate change on health and ecosystems and will include them in macroeconomic assessments. A distributional analysis of climate change impacts and policy will be developed, in particular conducting a systematic assessment of cost and effectiveness of adaptation.

Many studies have systematically analysed the impacts of climate change at the European level, both from the point of view of physical impact projections and with regard to their effects on economic systems, in the short, medium, and long term. Given the complex nature of climate phenomena and their interdependent interactions with human socio-economic systems, a continuous research development in this sense is necessary, also in light of the mitigation-adaptation pathways operated at the European and global level, and of the most recent improvements of impact assessment tools available.

The stocktaking and gap analysis provided in this report will be used as a basis to develop a comprehensive, updated and co-designed assessment of climate risks in a fully integrated framework. The most recent literature and update knwoledge on relevant sources of impacts have been analysed in a multi-sectoral and cross-regional European framework.

Besides many recent research works at the European level, results from some relevant european-funded projects were particularly taken into account, including: COACCH (H2020), NAVIGATE (H2020), SAM-PS (DG-CLIMA), REACHOUT (GD), RECEIPT (H2020), ENGAGE (H2020), TREEADS (H2020), DAMOCLES (COST Actions), REST-COAST (GD), CoCliCo (H2020), ENERGYA (ERC), CASCADES H2020, PARIS REINFORCE (H2020), LOCOMOTION (H2020).

Among these, the COACCH project (2018/2021) has certainly played a key role in assessing the impacts and costs of climate change in the EU, because of the comprehensive, multi-sectoral results obtained and the number of partners and stakeholders involved, both academic and institutional. The project developed a first assessment of the state-of-the-art knowledge[2] regarding the economic costs of climate change in Europe for relevant sectors and type of impact (Tröltzsch et al., 2018). The following major gaps were identified.

- **Agriculture**: Existing focus on medium to long-term productivity changes, with no analysis on inter-annual price fluctuations, e.g. from extreme weather events. Limited coverage on implications of yields and prices divergence from market equilibria, as well as welfare or profit implications along multiple scenarios and with uncertainty (multiple futures and costs). Need of capturing and designing robust adaptation responses especially in the long term. Limited coverage of the interaction between agriculture, forestry, and bioenergy into the mitigation policy assessment. Limited coverage of unexpected shocks in agricultural supply and markets, as well as long term tipping points.

- **Forestry and fisheries**: Need for further economic analysis of impacts on production, consumption and markets for forestry products, and land-use interactions with the agriculture sector. Gaps on the economic costs on wildfires, changes in pests and diseases and on wider ecosystem services, as well as large-scale

[2] A comparison table of the literature coverage on impact categories most relevant for the EU as individuated by COACCH (2018) and after most recent knowledge improvements is provided in Appendix A.

tipping points. Many gaps in the economic modelling on marine fisheries and aquaculture production, and in key effects such as ocean acidification.

- **Flooding**: Need to reconcile top-down and bottom-up (local) studies, improving model validation and the representation of adaptation (including costs and benefits), indirect costs and intangible impacts assessment. The existing focus on Expected Annual Damage (EAD) gives little insight into large extreme events with high policy resonance. Need to further analyse the relation between direct and indirect costs of flooding, especially in terms of critical infrastructure and built environment, and to advance surface flooding estimates.

- **Water supply and management risks**: Limited knowledge on climate costs for the water sector on EU level. Existing cost assessments especially for adaptation activities on regional, river basin or local level, partially including projection of damage costs. Need for analysis of cross-sectoral effect and potential cascade effects to all sectors, also integrating cumulative pressures, both from water demand and supply side. Need to further develop biophysical and hydrological models linked with economic assessments.

- **Coastal flooding**: Model improvements are needed for local differentiated sea level rise, improved resolution of population and elevation data, and downscaled consideration of major cities and ports. Need to integrate adaptation pathways and decision making under uncertainty into the European, and national scale models and strategies. Need to consider the economic, financial, and social barriers to adaptation, also extending the analysis of extreme scenarios to include socio-economic tipping points.

- **Energy**: Major gap exists concerning cooling demand, including the costs and benefits of adaptation options for cooling. There are gaps remaining also on the economic costs of weather extremes on hydropower, wind, and thermal generation, and overall energy security.

- **Transport infrastructure**: Need to improve the direct cost estimates for road transport and the costs of flooding for rail transport, as well as the methods to assess the indirect costs of transport disruption. Improving the economic costs assessment of climate change on critical transport infrastructure, including inland and marine transport hubs, and the analysis of indirect network effects. Need to advance cost-benefit analysis for adaptation investment decisions.

- **Health**: Good coverage of economic costs with focus on heat-related mortality, with gaps in the assessment of distributional impacts (between north and south), hot-spots and adaptation strategies. Key gaps in relation to vector borne disease and aeroallergens, as well as the potential impacts on health services and social care, and possible health tipping points.

- **Tourism**: Existing focus on summer beach tourism, but without integrating multiple climate impacts (productivity, coastal impacts, water) alongside temperature. Major gap for other tourism sectors, such as winter tourism. Further analysis is needed for adaptation strategies and costs.

- **Biodiversity and ecosystem services**: Consistent gaps in the estimates of physical impacts, including all aspects of the economic valuation of biodiversity and ecosystem services. Need 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, also considering possible non-marginal impacts and tipping points.

- **Business, industry, and trade including insurance**: Need to investigate supply chain effects, both in Europe and internationally, as well as trade implications on business, extending to macro-economic analysis and the effects on public budgets. Further analysis on shocks and tipping points on businesses, as well as climate change implications on EU insurance arrangements.

- **Macroeconomic, growth and competitiveness**: Need for consistent and harmonised European economic cost estimates, including disaggregated estimates at national and subnational levels; improvements in the interlinkages between process-based and sector analysis and the CGE models. Gap in the analysis on the impacts of climate change on growth rates (drivers of growth), sectoral differences, and changes in the level of competitiveness. Need to integrate trade and market effects, as well as representation of major extremes and tipping points.

- **Tipping points**: Several research gaps, especially regarding socio-economic tipping points. Need to categorise different types of socio-economic tipping points to estimate potential economic costs, also in relation to potential climate thresholds that could trigger these events.

While many of these gaps have been widely assessed by most recent European studies, some still remain open questions for future research.

The present report aims at providing the current state-of-the-art framework, underlying possible major research gaps and modelling improvements to be further assessed within ACCREU.

1. Agriculture, forestry, and fishery (including water management)

1.1 Agriculture

Agricultural land accounts for 40% of total EU land. Agriculture and food-related industries and services provide over 44 million jobs in the EU, and 22 million people are directly employed in the sector. Because of a favourable climate, technical skills and the quality of its products, the EU is one of the world's leading producers and exporters of agricultural products (Jacobs et al., 2019).

Climate change may affect the agricultural sector through direct impact (either positive or negative) on agricultural yields, or changes in available farmland for crop production (Van der Wijst et al. 2021). It can also affect production impacting the productivity of non-land inputs, primarily labour (Orlov et al 2021), or with shifts in the range and prevalence of pests and diseases (Tröltzsch et al. 2018). Indeed, crop failure is commonly induced by the occurrence of multiple and combined stressors, often leading to non-linear impacts (Goulart et al., 2021, Boere et al 2019). The magnitude of climate induced yield impacts highly differs across crops and regions within the EU. Accordingly, at the aggregated EU level, negative and positive effects tend to compensate, making it difficult to appreciate the severity of climate and economic risk. At the same time, it has been also noted that the relative change of climate impacts stayed relatively invariant across socio-economic storylines.

Going more into detail, Fernando et al. (2021) estimated a percentage reduction in the EU agricultural productivity of -1.96% as a consequence of droughts, -1.89% due to extreme temperature, -0.36% due to floods, -0.22% to storms, and -2.70% to wildfires.

According to Feyen et al., 2020, in the absence of adaptation, climate change is expected to lower grain maize and wheat yields in southern Europe by more than 10% in a 2°C warming scenario, and to a lesser extent grain maize yields in northern Europe. On the contrary, wheat yields are projected to increase by around 5% in the Northern EU.

Reduction in water availability for irrigation could reduce European maize yields by 80% in 2050, in Portugal, Bulgaria, Greece, and Spain (Hristov et al. 2020). Increased climate related stress could also cause the abandonment of farmland in Southern Europe with farmland values projected to decrease by 5–9% per degree of warming (Bednar-Friedl et al. 2022).

Orlov et al. 2021, provide projections for the integrated climate-induced impacts on crop yields and worker productivity[3] on the agro-economy in a global multi-sector economic model. They show that even though CO2 fertilisation effects could increase crop yields, the negative impact of heat stress on workers' productivity overcompensates that by inducing a net decline in agricultural output.

Fujimori et al., 2021, underline potential adverse impacts of land-related emissions mitigation strategies on food security at a global level, particularly due to food price increases in relation to afforestation. This highlights the need for better coordination across emissions reduction and agricultural policies as well as better representation of land use and associated greenhouse gas emissions in modelling.

Finally, the CASCADES (2020) project shows that declines in EU agricultural production can be triggered by adverse competitiveness effects induced by climate change impacts outside the EU. In 2070 under RCP6.0, EU loss of competitiveness can lead to a decrease in rice production, reaching -8% in the Mediterranean and -15% in the Eastern EU. Concurrently, EU rice exports can decline between 25% and

[3] For a detailed report on labour productivity impacts see section 5. Business, industry, trade, and supply chains.

46%, while the production of other cereal crops is less affected. The loss of competitiveness also explains a simulated 13% and 3.6% contraction in oil seeds and sugar cane and beet production, respectively, in EU Mediterranean regions and a concurrent 17% and 6.5% decrease in exports of these two crops.

Economic impacts in the agriculture sector

The total economic loss for agriculture in Europe due to climate change are significantly influenced by market mechanisms (e.g. changes in crop prices, substitution of factors and changes in competitiveness in response to yield changes), which can soften or strengthen the initial biophisical impacts on agricultural production (Martinez et al., 2017; Jacobs et al., 2019). However, **uncertainty** on the nature of cross-border climate impacts, their severity, and the way in which responses might manifest, is still high and studies highlight quite different economic findings. Furthermore, the agricultural sector builds a low share of total value added in the EU (2,5%). Accordingly, macroeconomic assessments tend to quantify moderate to small macroeconomic effects triggered by dynamics in the agricultural markets.

Hristov et al. (2020), show that the interplay between changes in agricultural production in the EU and other major cereal producing countries that could be damaged more severely by climate change, may in fact lead to EU export increases in wheat, barley, grain maize and soybean, with the EU producer prices increasing between 1% to around 7%. This can result in increases in the EU producers' income between 25% and 50% in Northern Europe and 10% to 30% in Southern Europe.

On the contrary Boere et al. (2019) shows that EU cereal producers will experience €1.7 billion of losses under RCP4.5 in 2050 with corn production representing up to a third of the agricultural losses. According to the authors these costs should be interpreted as lower bounds for the economic losses as the study does not cover all crops produced in the EU, notably fruits and vegetables.

Bosello et al. (2020) perform a sub-national macroeconomic assessment of climate change impacts in the EU, detailed at the NUTS2 administrative level. They find rather limited macroeconomic effects from climate change impacts on agriculture on EU national economies. However, they identify many regional hotspots for economic losses located in southern EU countries such as Spain, Italy and France where regional gross domestic product can decrease from 2.5 to 5% in 2050. In the high impact on yield case, regional GDP losses start to appear in 2030 and in 2070 they can range from 5 and 10%. The regional assessment also shows positive economic effects in the agricultural sector in the north-eastern EU.

Using a Ricardian approach van Passel et al. (2017) estimate potential decrease in farmland value from climate change in the Southern EU peaking to -9% in Greece and Portugal, and improvements in the Northern EU especially in Sweden and Finland, where land value is projected to increase by about 16%.

Other studies highlight much lower macroeconomic impacts.

For instance, according to the CASCADES project (2022) in 2070 under RCP6.0, these impacts range between a -0.03% change in GDP in the Northern EU to +0.08% in the Eastern EU. Cross-border trade effects seem more relevant than the direct effects on yields to determine the GDP performance.

Gouel (2022) estimates a -0.18% GDP loss in RCP8.5 in the 2080s in the EU with a maximum -0.74% in The Netherlands. while other countries show small gains such as France with 0.05% of GDP.

BOX 1.A Soil erosion and climate change

A separate discussion deserves the relationship between land degradation and climate change. This issue is gaining more and more importance since the approval in July 2023 of the European “Nature Restauration law”, as one of the key pillars of EU Green Deal and the Fit for 55 Program. An effective soil management – preserving soil quality ‐ is of key importance as soil performs several important functions: it supports food production, water storage, biodiversity conservation and carbon storage and also provisioning ecosystem services (IPCC, 2022). The ability of soil to perform these services is reduced when it is degraded (its quality is reduced) or eroded (its quantity is reduced). Climate change can potentially impact soil quality and quantity through many channels, for example, precipitation extremes can reduce soil biological functions, and increase surface flooding, waterlogging, soil erosion and susceptibility to salinisation. The loss of Soil Organic Matter (SOM) and Soil Organic Carbon (SOC) storage are particularly threatened by climate change

(IPCC, 2022; Jacobs et al., 2019). While the land degradation process due to soil erosion (i.e. the rate of soil loss exceeding that of soil formation) is a natural process, it is becoming particularly severe in the Mediterranean zone and some Alpine regions, with impacts on food production, drinking water quality and biodiversity (Jacobs et al., 2019). While most of soil loss in Europe derives from erosion by floods and rainfalls (Panagos et al., 2015), agricultural activities can accelerate this problem (Jacobs et al., 2019) when soil management practices are not taken into account. Agricultural lands (about 47 % of the EU surface area) showed a mean soil loss of 3.24 t/ha per year (based on 2010 as reference), amounting to 68.3 % of total soil losses in the EU (Panagos et al., 2015).

Panagos et al. (2018) estimate that more than 12 million hectares of agricultural land in the EU (about 7.2% of the total) are potentially severely eroded every year (reference period 2010), with almost 3 million tonnes of wheat and 0.6 million tonnes of maize being estimated to be lost annually due to severe erosion. The highest productivity loss is found for rice and wheat because they are the most dominant crops in the most erosive areas of Mediterranean countries (Italy, Spain, and Greece). Consequently, the total economic loss in agricultural productivity due to severe erosion in the EU is estimated around €1,25 billion (reference year 2010), which is about 0.43% of the EU's total agriculture sector contribution to GDP (estimated at €292,3 billions). Accounting for the macroeconomic impact, the estimated annual cost for the agricultural sector is around €295 million (-0.12%), leading to a GDP loss of around €155 million/y. The fact that loss in crop productivity is much higher than the loss in the agricultural sector and the overall GDP loss is due to endogenous adjustments in the economic system through trading mechanisms which mitigate initial losses in production.

Projections show that in the agricultural lands of the EU plus the UK, the mean rainfall erosivity 2010–2050 change varies from +22 % in RCP2.6, +23.9 % in RCP4.5 and +36.9 % in RCP8.5 scenario (Panagos et al., 2021). Despite this, the literature reporting the projected economic loss in terms of agricultural production and GDP of soil erosion and land degradation seems to be little, especially if related to the potential impact on agricultural productivity. Some indicative estimates would indicate potentially large economic costs for the EU, in the order of € hundreds of millions/year. However, the effects of multiple climate change impacts on soil, including vegetation cover and soil processes, are not sufficiently well understood to project the detailed monetary effects of climate change (COACCH D4.2, 2022).

The impact assessment of climate change-driven soil erosion, in particular related to agriculture, needs to be further assessed by future research.

Adaptation: costs and effectiveness

Adaptation in agriculture can consist of i) **autonomous (sometimes called endogenous), reactive adaptation measures:** altering sowing and harvest dates, reallocation of crop cultivations, adoption of different rotation shifters, crop selection, water reallocation among crops, changes in irrigation patterns, implementation of soil water saving techniques; ii) **autonomous proactive adaptation measures:** requiring planned investments or changes in the production structure (e.g. implementation of different irrigation methods, introduction of more efficient production methods).

Proactive and reactive adaptation in agriculture can be also public/planned, when action is promoted by public agencies or administrations. Measures at national and regional level can range from publicly provided climate services improving weather/climate information (including early warning systems to farmers), to supply and demand management of water resources and flood prevention, to establishing public research programs (i.e., for climate resilient crop varieties). Subsidies/taxes can also encourage the desired modifications of farming practices like increased pesticide control, or agricultural systems with lower GHGs emissions and more efficient irrigation systems (Bindi & Olesen 2011). Overall, planned adaptation in the agricultural and forestry sector seems less firmly established than in other cases (i.e. as for flood protection), with adaptation concerns being mainstreamed into already existing policies and funding programs, under a distinct influence of EU policies (Van der Wijst et al. 2021), in particular the common agricultural policy (CAP). An example is the 2013 EU adaptation strategy, a key EU-level driver of adaptation aimed to promote adaptation in the agriculture sector within the CAP. The new EU strategy on adaptation has been adopted in 2021, and it is embodied in the new CAP for 2023-2027, which has adaptation as a clear objective, possibly leading to Member States having to increase their financing of adaptation measures in the sector (Jacobs et al., 2019). Within this, direct payments support as well as some rural development interventions are conditional to environmental and climate change standards and requirements. An important novelty is a requirement to strengthen efforts for environmental and climate change mitigation and adaptation in the fruit and vegetables sector. This is through attributing 15% of expenditure of operational programmes to include such actions and 5% of expenditure to strengthen research, development and innovation actions. However, while there are 59 agri-environment management commitments from 21 Member States planned linked to climate adaptation, only two Member States (BE-FL, BG) are funding climate /drought resilient crops or varieties through agri-environment interventions (CAP, 2023).

In addition, international trade can in some cases play a role in helping countries to adapt to climate change impact on agriculture (Stevanović et al., 2016; CASCADES, 2022), and also contribute towards adjusting agricultural production in an efficient manner across countries (FAO, 2018). Nevertheless, the extent to which this can happen depends on how economic scarcity or abundance translates into price changes across markets, and on market openness. An orientation towards trade liberalisation, if regulated and compatible with the environment, climate and sustainability objectives, could facilitate the introduction of adaptation (Jacobs et al., 2019).

Beyond adaptation per se, agricultural producers often purchase crop/yield insurance to protect themselves against the loss of their crops as a result of natural disasters (mainly hail, drought and floods), limiting the worst effects of climate impacts. As premiums for agricultural insurance are quite high, many countries may subsidise such insurance (Jacobs et al., 2019).

Assessing “in aggregate” the **effectiveness of adaptation** in agriculture is extremely challenging as it varies greatly across crops, geographical areas, and, of course across the different typologies it can take (Boere et al., 2019; Feyen et al., 2020; Van der Wijst et al., 2021; IPCC AR6 WGII, 2022).

For Europe, changing sowing dates and the crop variety sown, would probably not suffice to offset the projected reduction in grain maize yields, while changing varieties could have a much larger beneficial effect on rain-fed wheat production. Plant-breeding can identify ‘faster’ wheat varieties, which may lessen the projected yield reduction from climate change and in some cases even give rise to an increase in yields. Implementing irrigation infrastructure, can also pursue the same objective (Feyen et al., 2020; Hristov et al., 2020).

In a similar vein, Boere et al. (2019) show that in the EU28 the best reply to corn yield reduction is an increase in the cultivated area, even though this may not be enough to compensate for the loss in production. On the contrary, in the case of wheat, other types of adaptation can be extremely successful, and the consequent increase in the yields leads to a decrease in the cultivated area, even though in the case of RCP2.6 and RCP6.0, this decrease in the area is larger than the increase in the yield.

Moreover, countries like Spain, where the major hazards are more frequent droughts and heat spells, investment in capital intensive improvement and expansion of irrigation infrastructure can be more appropriate than in countries like Austria where it can be sufficient to promote a shift towards more resilient crop and tree species (Van der Wijst et al. 2021).

While most of the impact studies on agriculture have focused on production and yield changes, **economic assessments** of the effectiveness of adaptation, namely the ability of adaptation to reduce economic impacts, are scarcer. Among the few studies Balkovic et al. (2015) find that adaptation may overcompensate economic losses from climate change in all land-use related sectors in Europe (leading to a net benefit).

At the macroeconomic level, adaptation has been shown as an effective measure in reducing the negative sectoral and economy-wide effects, while in some cases (i.e. Spain), net output losses remain, given that productivity losses cannot be prevented completely by assumption, and the increase in irrigation infrastructure makes agricultural production more expensive (Van der Wijst et al. 2021).

Key gaps

Better understanding of the source of uncertainties:

- High levels of uncertainty characterise the entire impact assessment chain, from climate model uncertainty to crop model uncertainty, resulting in significant differences in climate-induced impacts on crop yields across simulations (Boere at al., 2019; Orlov et al. 2021; Ebrey R. et al., 2021).
- When comparing the relevance of different types of modelling uncertainties, the largest part of uncertainties is attributed to climate models (GCMs), particularly in the transient **climate response** to cumulative CO2 emissions.
- Crop models present uncertainties in the **exposure–response functions**, and in presence of socio-economic uncertainties, with considerable differences in models' reaction to different RCP and SSP scenarios, also due to potential **shifts in diets habits**.
- The **epidemiological exposure–response relationship** is also very uncertain since the calibration is often based on a limited number of studies. Further research is needed to account for climate-induced effects such as pests and diseases.
- The impact of **CO2 fertilisation effect** for high climate signal scenarios (RCP8.5) may result in a source of uncertainty since it smooths yield losses and often transforms them into gains.
- Bio-economic models may present **regional inconsistencies and uncertainties** across models since large parts of economic estimates are not driven by absolute change in climatic conditions, but by relative **changes in market competitiveness.**

Better representation of key inputs in models:

- Biophysical and bio-economic models could be improved by accounting for a better representation of climate induced effects such as **pests and diseases**.
- The majority of crop simulation models are developed to simulate herbaceous annual crops and few attempts have been made to simulate **perennial tree crops** (i.e. grapevine and hazelnut) to cover all crops produced in the EU, notably fruits and vegetables, this leading to costs underestimation.
- The implications of **potential shifts in diets**, which could significantly differ by SSP scenarios, needs to be further explored.
- Alongside the economic response to long-term trends in climate variables, focusing on **single extreme events** such as hail or storm and **compound events** could be an avenue for future research, as well as **inter-annual price fluctuations** (i.e. from extreme weather events).
- Relevant cross-sectoral impacts (i.e. between forestry and agriculture) shall be accounted into bio-economic models (notably partial equilibrium models).
- Estimates of climate change impacts on **soil degradation** in Europe, and related future economic costs, need to be implemented in models.

Better understanding of regional differences:

- Both biophysical and economic models' results comparison do not often allow to identify robust **regional land use patterns**, and regional differences are most likely to be attributed to the upstream crop model disagreements (Boere at al., 2019).
- Regional economic impact estimates driven by relative competitiveness within the local region and the world market may present high uncertainty as they do not account for **non-adaptive supply chains with regional specialisation.**
- More research is needed to derive region and sector specific exposure-response functions for **heat stress impacts** (Orlov et al., 2021).

Better representation of adaptation patterns and costs:

- The degree to which producers can adapt to climate change needs to be further researched, accounting for **relevant rigidities in adaptation** and including deep capital stocks in agriculture, lost experience of farmers under changing climatic conditions, and non-adaptive supply chains with regional specialisation.
- **How rapidly and at which costs** farming systems can adapt to new climatic conditions (i.e., changes between crop types and cultivars) is a topic that requires further attention and interdisciplinary research.

- The implication of **proactive investments in mechanisation** and R&D (i.e., robotisation) diminishing the adverse impacts of heat stress needs to be further explored.

Household dimension needs to be further assessed:

- When looking for climate impacts, the main research is often about wide economic sectors impacts or aggregated damages across countries. A key gap has been found in the distributional consequences across households and private business, including fiscal and financial implications.

BOX 1.B Models and Methods

Crop Simulation Models (CSMs) simulate crop growth development and yield through mathematical equations as functions of soil conditions, weather/climate, management practices and crop genetic characteristics. Several types of CSMs are used to reproduce and analyse various processes, including changes in the soil carbon concentration, greenhouse gas emissions, plant breeding, resource use and efficiency of water and nutrients, and crop yield. They predominantly focus on the assessment of climate change impacts than on the evaluation of adaptation options (Ebrey R. et al., 2021). They can also be applied to evaluate the effects of alternative management strategies under different environmental conditions (Mereu et al., 2019). Following this, the subsequent alterations in temperature and precipitation and their impact on crop yields can be examined using either **statistical models** (Sun et al. 2007; Chen, McCarl, and Schimmelpfenning, 2004; Ray et al. 2015), which use reduced-form equations to estimate the effect of historical temperature and precipitation data on yield variability (Mistry, Wing, and De Cian, 2017). **Biophysical process-based crop growth models**, along with their gridded derivatives known as the Global Gridded Crop Models (GGCMs), aim to model key processes affecting plant growth dynamics, by simulating a wide range of exogenous variables such as weather, plant genotypes, environmental factors and management styles on plant growth (Tröltzsch et al. 2018) and allowing them to analyse crop and management options under different climate patterns (Hatfield et al., 2011; Pathak & Wassmann, 2009; Rosenzweig et al., 2013). Lobell & Asseng (2017) made a comparison of the two methods, finding that for larger warming, systematic differences are observed because process-based crop models typically include CO2 effects of global warming, whereas statistical models typically do not. **Partial equilibrium (PE)** and **Computable General Equilibrium (CGE) models** can be used to represent the influence of yield changes on agricultural markets, as well as various econometric approaches or simulation models (van Meijl et al., 2017; Wiebe et al., 2015; Bosello et al., 2021; CASCADES, 2022). Only a few of these models attempted also to analyse the effects of extreme weather events. One of these models is GLOBIOM in which annual weather variability and climatic shocks will result in deviations from expected prices and yields (Boere et al., 2019).

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1.2 Forestry and fishery

Affecting the rate, frequency and intensity of extreme events, climate change impacts on forest and marine ecosystems are expected to increase over time, driving complex and partially opposite regional effects.

Forestry

Forestry is a sector with long production cycles, and thus highly exposed and vulnerable to climate change (Boere et al., 2019). The net effects of climate change on forestry are complex. Tree growth could be favoured by some climate change induced factors, such as CO2 fertilisation, warmer winter weather, and longer growing seasons, inducing increasing harvest potentials. Other aspects could negatively affect forestry, such as decreased precipitation and extreme weather events (e.g. storms,heat waves) . Drought also makes forests more susceptible to additional risks associated with fires, which can affect both managed and natural forests (Tröltzsch et al., 2018; Boere et al., 2019). Results by Williams et al. 2019 show a strong exponential relationship between forest drought‐stress and satellite measurements of forest and woodland area burned by wildfire. They suggest that if the vapour‐pressure deficit continues increasing as projected by climate models, the mean forest drought‐stress by the 2050s will globally exceed that of the most severe droughts in the past 1,000 years, this leading to a severe increase of fire hazard. Climate change can also lead to increased vulnerability due to invasive species and plant diseases.

Studies show that optimal altitude for forest species is changing on average about 30 m (with the range of -170 to +240 m for different species) per decade in France and Spain (Bastrup-Birk et al., 2016).

All these compounded effects may advantage forests' ecosystems in some parts of the EU, but be highly detrimental in others. Results from Boere et al., 2019 (COACCH D2.2), estimate that, due to climate change, Northern parts of Europe will increase their forestry areas. However, increased temperature and decreased precipitation may 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. Climate-induced interactions between the agriculture and forestry sectors are shown to be of limited magnitude.

Fire hazards represent a major risk that has been affecting southern Europe more drastically compared to the Northern regions. Nearly 1 million hectares of land was burned in Europe in 2017, compared to an average of around 213,000 ha between 2008 and 2016, and the number of days with high-to-extreme wildfire risk is projected to increase as temperatures rise to 2 °C and 3 °C, with fires worsening in severity and size (Costa et al. 2020). In July 2021, the Mediterranean region was experiencing its worst heatwave in decades and a total of 1.113.464 hectares were scorched by fires in 43 European countries (500.566 for EU27), from Turkey to Spain. About 25% of the total burned area belonged to crop lands while forests accounted for 28% (San-Miguel-Ayanz et al. 2022). Turkey and Italy were the most impacted nations, with respectively 206,013 ha and 159,537 ha of burned area, Spain was close by with 901 fires that burned a total of 91,295 ha, with large shares of fires occurring in protected regions, putting at risk endangered plants and animals. Beyond important ecosystem losses, the destruction of extensive forest areas in Greece is expected to lead to even higher temperatures, desertification, greater exposure to natural hazards and loss of agricultural production affecting lives and livelihoods (IFRC, 2021; Niggli et al., 2022). Similar and maybe even worse situation[4] occurred also in summer 2023 in many southern European countries, particularly in southern Italy, Spain and Croatia.

Findings from Boere at al. 2019, estimate that the potential burned area in Europe will increase significantly in Europe especially under the RCP8.5 scenario, potentially more than double compared to present-day, which could increase associated costs. The regions with the highest shares of burned areas are found to be Portugal, Spain, South of France and Greece. Since a sizable portion of Mediterranean Europe will experience drier extremes in the deep fuel and Spain, Portugal, Turkey, Greece, a portion of central and

[4] At the time this report is written, data on the overall impact of 2023 fires are still not available.

southern Italy, and Mediterranean France are the nations with the highest wildfire risk (Ciscar; et al. 2018; De Rigo et al. 2017).

In the assessment of socio‑economic tipping point from **major blackouts due to increasing wildfires**, Botzen et al., 2020 (COACCH D3.4) show that much of the land area in Europe could see extreme increase in wildfire probability by the end of the century under different RCP scenarios, including areas which until now have little experience dealing with such threats. Wildfire impacts and associated blackouts additionally can impact private households via loss of property and life.

Fishery

Climate change can generate various adverse impacts on aquatic systems, vulnerable fisher populations and associated industries relying on fisheries, but can also create potential opportunities in some regions (Galappaththi et al., 2021). Changes in temperature and water composition play a key role on the health and productivity of various aquatic species. These factors are affected by climate change through many different channels: changes in temperature and ocean chemistry (e.g. ocean acidification) directly affect the physiology, growth and reproduction of aquatic organisms (Sumaila et al., 2011), while higher occurrence of storms and extreme weather events (e.g. marine heatwaves), and sea level rise may affect coastal fish habitats as well as aquaculture infrastructure (Boere et al., 2019; Galappaththi et al., 2021). Moreover, pollution from boat traffic and human development, on top of climate change, can have a combined influence on fisheries and their adaptive capacity (van Putten et al., 2013, 2016).

Climate change will bring about alterations in both the **abiotic aspects** (e.g., sea level, sea temperature, oxygen levels, salinity) and the **biotic aspects** (e.g., primary production, food webs) of oceanic conditions. Consequently, marine organisms' reproductive success, growth, size, and disease resistance will be affected. Similar risks exist for freshwater fisheries and aquaculture. Fish populations may migrate into colder, deeper water and from coastal waters towards the oceans to avoid warm temperatures, while changing habitats may increase the risk from invasive species with negative effects for marine biodiversity (Worm et al, 2016). Meridionalization (occurrence of warm water species in northern regions) and tropicalization (expansion of non-native tropical species) in the Mediterranean, and the spreading of Mediterranean species in colder seas, are strengthened by warming and will have positive and negative impacts on fisheries (Hidalgo et al., 2019).

Human fishing activities are the dominant factor impacting the abundance and distribution of numerous marine organisms in European waters. Nonetheless, climate change adds extra pressure on fish stocks that are already showing a low resilience and limited regenerative capacity (Boere at al., 2019). Furthermore, climate change risks extend beyond marine ecosystems to freshwater fisheries and aquaculture (Ficke et al., 2007; Cochrane et al., 2009). Impacts of climate change are already observable in the European Seas.

Bednar-Friedl et al. (2022) project a reduced abundance of most commercial fish stocks in European waters of 35% for scenarios between 1.5°C and +4.0°C. Boere at al., (2019) indicates that, notwithstanding fish species near the equator are affected more negatively, also all EU Member States are projected to experience **declines in marine productive capacity**, especially in Denmark, Spain, France, and the UK. The EU28 is estimated to lose from 3 to 9 million tonnes in annual catches by 2050, without considering the potential negative impacts stemming from marine extremes and ocean acidification. As the EU capture fisheries rely on several large marine ecosystems, the EU as a whole may benefit from climate change, possibly developing a relative advantage, as total global capture fishery potentials will decline. Without accounting for aquaculture, a decline in total marine fish catches would probably have limited effects on the land management, as marine capture fish demand represents only a small share of total animal calories consumed worldwide (Boere et al., 2019).

Climate change presents both challenges and opportunities for the sustained production of farmed aquatic food and those engaged throughout the value chain (Soto et al,. 2019). While the aquaculture sector is often assessed together with fisheries or agriculture and in coastal or watershed-based studies, the sector's vulnerability must be complemented by investigations at more localised levels, where specific aquaculture practices, environmental conditions and interactions with stakeholders and communities are taken into account. Few studies (Soto et al,. 2019; Blanchet et al., 2019)suggest that relative vulnerability to climate change for European aquaculture seems to be low to very low both for aquaculture in freshwater and for the one in the marine environment. Some relevant exceptions are Norway, Greece, Croatia and Cyprus, which can experience vulnerability levels for marine aquaculture from very high to medium, respectively (Soto et al,. 2019).

Economic impacts on forestry and fishery

While ecosystem services (ES) from mountain forests are highly relevant for human societies with a direct economic support function (e.g. timber production), regulatory services (e.g. protection from natural hazards) and cultural services (e.g. recreation) (Mina et al., 2016), forestry in the EU represents only a small share of aggregated value added. The same applies for fishing activities. In 2022, the relative contribution of agriculture, forestry and fisheries to gross value added in the EU economy stood at 1.9 %. Still the economic consequences from climate change impacts to these sectors can be quite relevant. Boere et al., (2019) find economic **losses in the forestry sector in the EU** in the order of 63 million Euros for producers and 670 million Euros/year for consumers in RCP8.5 .

In the RCP8.5, in 2050 producer losses in the fishery sector (also accounting for aquaculture) can amount to 1.3 billion Euros/year for Europe, mostly related to a decrease in capture production (Boere et al 2019).

Other macroeconomic dynamics can be associated with these impacts. Bosello et al. (2020) suggest that the **price of timber and fish resources is expected to increase** over time more than that of capital and labour. Fish and wood resources thus become more important in relative terms in value added. Accordingly, when these resources are hit negatively (or positively) by climate change impacts, effects on regional GDP can be substantive. Also trade effects play an important role. For instance, the study shows that in 2050 Finland, Northern Sweden and Latvia may experience losses slightly larger than the 1% of their regional GDP. At the same time, international trade matters. The study hints that by the end of the century, EU regions can, with few exceptions, experience gains in the order of 1-2% of the regional GDP. In fact, while direct impacts of climate change on fish stocks are negative, these can be lower than in non EU areas giving EU producers a competitive advantage.

Other important costs, indirectly related to the forestry sector and forest management are those associated with **wildfire hazard**.

Forest fires damages in Europe were estimated at €1.5 billion in 2010 (San-Miguel-Ayanz et al, 2010), while between 2010 and 2018, Southern Europe suffered losses between 12.8 and 20.9 billion euros per year (Meier et al. 2023). Given the nature of the two most important driving forces for fire hazards, periods with below-average rainfall and occasional strong heat waves exponentially increasing the availability of dry fuel for wildfires, impacts on society and economy in Europe are likely to increase (Botzen et al., 2020, COACCH D3.4). Considering that Europe is a highly populated area where many people live close to forests and wildland, wildfires increase results in a significant risk for agricultural resources and urban areas, with serious ramifications for the protection of economic assets, the provision of essential services, and the safety and health of citizens (Costa et al.2020). Niggli et al. (2022) find that in the 2003, 2015 and 2018 extreme fire events across Europe, among the most impacted sectors were human health, water resources, agriculture and food production, energy, transports, economy and financial system, ecosystems and culture.

A recent study by Meier et al. (2023) estimated the economic impacts of wildfires in terms of GDP and employment losses across European regions. Using annual regional economic data on employment and GDP growth from 2010 to 2018 together with satellite imagery of burned areas, the research focuses on the regions more at risk of fire hazards in Europe such as Portugal, Spain, Italy, and Greece. What emerged by looking at the data collected is that additional fire hazard can reduce the region's yearly GDP growth rate by 0.026% on average (the worst observed year in the sample period showed annual GDP growth decrease of 3.3%). Overall, for Southern Europe, wildfires have a persistent negative modest impact on the annual regional GDP growth rate, which ranges from 0.11 to 0.18%. In terms of employment rate, considering the direct impacts on tourism, industries like wholesale and retail trade, transportation, lodging, and food service activities are facing a negative employment effect of 0.09-0.15% resulting in an average loss of 5,712 to 9,588 jobs in a year for Southern Europe. Whereas wildfires can have a positive impact on regional employment growth of 0.13 to 0.22% in industries such as finance, insurance, and real estate as well as short-term contracting activity resulting in annual increase of 4,284 to 7,242 jobs in Southern Europe.

Adaptation: costs and effectiveness

Forestry

Adaptation of forest management to climate change requires an understanding of the effects of climate on forests, industries and communities (Keenan, R.J., 2015). Because of the economic and ecological relevance of forests, it is of fundamental importance to apply appropriate forest management to make forests able to cope with the new environmental conditions (Busotti et al., 2015). Adaptive strategies may include: (i) persistence of the current forest types, thanks to the autonomous acclimatisation to local conditions due to phenotypic plasticity (Nicotra et al., 2010) of the populations (the ability to change in response to stimuli from the environment, allowing responses to rapid climate fluctuations); (ii) evolution, or local adaptation (Hoffmann, Sgrò, 2011), i.e., selection of new genotypes of the same species (or hybridation) better coping with environmental pressure; (iii) assisted migration (i.e., the use of species suitable for the future climatic conditions) and, alternatively, substitution of native with non native species. These strategies can however come into direct or partial conflict with national biodiversity goals and initiatives to restore habitat availability in production forests (Felton et al., 2016).

Under the new common agricultural policy (CAP) 2023-2027, most Member States schedule support for forestry, including an increase of the forest or wooded areas, agroforestry, restoring forests after natural disasters and adverse weather, and improving forest infrastructure for the sake of climate change adaptation. This is accompanied or complemented by area-based support for the sustainable management of forests.

Specifically regarding **fire hazard**, adaptation actions to reduce fire propagation and ignitions can consist in mechanical clearing, prescribed burning, land and vegetation management activities, as well as increasing citizen's awareness and preparedness. Without adaptation, under a +4°C scenario, Khabarov et al. (2016) estimate a potential increase in burned areas in Europe is about 200 % by 2090 (compared with 2000–2008), while the application of prescribed burnings has the potential to keep that increase below 50 %. Improvements in fire suppression might reduce this impact even further, up to a 30 % decrease in annual burned areas. Therefore, regional policy makers will need to evaluate strategies of mitigation and prevention mechanisms, as well as additional costs arising (Meier et al. 2023), also for human intervention to help precious ecosystems recover after a fire (Costa et al. 2020). Examining the social and economic factors that influence fire starting, promoting moral conduct, and punishing offenders are also ways to prevent an increase in the devastating impacts of forest fires on ecosystem health and biodiversity (de Rigo et al. 2017). Southern regions in Europe are the ones most affected by climate change and most of the time these are also the most economically vulnerable regions, with reduced adaptive capacities. Therefore, if no local adaptation strategies are put into place, the disparities between Southern Europe and Northern Europe will risk growing even more, given that under high climate change scenarios as RCP8.5, fire protection efforts could more than double compared to the current day (Boere at al., 2019).

Fishery

Accounting for adaptation in marine fishery, three main categories of adaptive responses can be underlined (Galappaththi et al., 2021): i) coping mechanisms (e.g. changing fishing location, targeting other species, using different gear, and decreasing/increasing fishing days and time on fishing grounds); ii) adaptive strategies consisting in long-term responses or shifts in livelihood strategies (e.g. livelihood diversification, incorporation of technology); iii) management responses involving planning, coordinating, organising and monitoring at various scales (e.g. adaptive management, adaptation planning, community-based management and government support).

Strategies may also need direct technical actions that enhance the resilience of socio-ecological systems, such as the construction of hard structures (e.g. sea walls), while others have less impact on local ecosystem processes such as the living shorelines approach, restoration of buffer areas or appropriate ecological corridors in habitats that have been badly fragmented. Some adaptive measures aimed at limiting the impact on economies may include re-adjustments in the insurance market, post-disaster recovery plans combined with political and economic plans for impact compensation, but also the enhancing of aquaculture-related activities or non-fisheries economic activities such as tourism (Hidalgo et al., 2019).

To address adaptation in aquaculture, it is necessary to understand its vulnerability and be able to identify major drivers and general exposure to climate change, which elements are often related to local dynamics, from the point of view of the type of species farmed, sector specificity and the different impacts of climate change in relation to these elements (Poulain et al., 2018; Soto et al,. 2019). As an example, reduced availability and quality of freshwater due to climate change may lead to increased competition among water users. Water consumption by aquaculture can be reduced by a series of technological or managerial innovations but ultimately, the involvement of stakeholders in the development of coherent policy, legal and regulatory frameworks is essential for effective decision-making on future food-water scenarios and water allocation decisions (Beveridge et al., 2018).

At European level, fisheries was included as a key sector into the 2013 EU Adaptation Strategy, while the European Maritime and Fisheries Fund (EMFF) has started to prioritise climate change adaptation and mitigation efforts to promote sustainable and resource efficient fisheries (Bryndum‐Buchholz et al., 2021). Among these, the facilitation of stock recovery and ecosystem resilience through temporary or permanent termination of fishing activities, with diversification and financial compensation funds for fishing communities impacted by such actions (European Commission, 2015). Finally, as part of the European Green Deal and its Farm to Fork Strategy, efforts have been included to rebuild fish stocks to sustainable levels and to re-assess how climate change adaptation is being addressed within the EU's Common Fisheries Policy, which indicates a move towards climate-informed management (Bryndum‐Buchholz et al., 2021).

Despite the relative importance of fisheries for our economy and food system in general, to the best of our knowledge, and excluding trade effects (market endogenous adaptation), no data are available at European level on the cost and effectiveness of adaptation strategies.

Key gaps

Forestry:

- **Better evaluation of non-monetary values and ecosystem services** needs to be implemented into cost benefit and cost effective analysis on forestry sector and forests in general, up to now mostly relying on macroeconomic assessment.

- **The understanding of adaptation strategies** and relative potential costs and benefits needs to be further assessed, particularly regarding fire hazard.

- **The increasing importance and frequency of wildfires** and the associated hazard for economy and household need to be better assessed, both from direct and indirect perspective (i.e., the expected losses occurring in the tourism sector, that could be particularly relevant in heavily affected regions).

Fishery:

- **Specific effects on fish species** of climate change have different impacts (as temperature and ocean acidification) needs to be further studied, as each species will react differently to climate modifications.

- **Cascade effects in marine ecosystems** (i.e., a decrease in the population count of one species could benefit the presence of another) and large scale effects of climate change on biodiversity (i.e., species migration) need to be implemented in the fishery models. Models shall incorporate how the biodiversity loss could subsequently affect fish populations, to capture ecosystem resilience.

- Up to date, most fish models assessing future capture projections are based on historical trend data for specific fish species at specific locations; more effort shall be made to **endogenously model** future trends in fishery capture production.

- **Better understanding of the role of aquaculture** in the fishery industry and its possible development in future climate change scenarios are needed, also accounting for possible shifts into diet habits under different SSPs.

- **Adaptation strategies and evaluation of relative costs and benefits** in fishery are poorly covered by present literature.

BOX 1C. Models and Methods

Forestry models investigate the dynamics of forest ecosystems under various environmental conditions, natural disturbances and anthropogenic management, including the impacts and adaptation responses to climate change and can inform decision making regarding forest growth, carbon sequestration and sustainable management (European Commission, Ebrey R. et al., 2021). Forestry models can help in examining forest ecosystem dynamics in relation to their structure and functioning, including forest growth and species composition (Grebner et al., 2013; Pukkala, 2018), evaluating the impacts on changing ecosystem services provisioning, including the hydrological cycle, bio-geochemical cycles and carbon sequestration (Pan et al., 2011), and assessing the effect of forest management practices, such as thinning and pruning, for sustainable use (Mönkkönen et al., 2014; Montoro Girona et al., 2017). Several modelling methodologies are used to assess the impacts of environmental and climate conditions on forest productivity, as well as suitable forest management practices which promote climate adaptation (Fontes et al., 2010). Forest dynamics can be modelled using process-based models which explicitly simulate physiological processes such as photosynthesis, transpiration and respiration and account for limiting biotic and abiotic factors and processes which influence long term forest population dynamics, such as establishment, growth, survival and tree mortality (European Commission, Ebrey R. et al., 2021), while empirical models are typically based on statistical analyses and relationships significant to forestry commercial management objectives, in particular related to the sustainable management of forestry targets such as timber production and biomass growth (Andrés et al., 2004; Pretzsch, 2009).

Regarding fishery, several global and regional studies have been carried on changes in annual catch and the redistribution of stocks or catch potential (Cheung et al., 2009; Cheung et al., 2010; Cheung et al., 2013; Blanchard et al., 2012; Merino et al., 2012; and Barange et al., 2018). The main approach used for fisheries are physical modelling using ecological trophic modelling (Tam et al., 2008); statistical analysis (Gephart et al., 2017); statistical forecasting (Klyashtorin, 2001); time-series analysis (Britten et al., 2015); GIS based analysis (Handisyde et al., 2006) and a number of coupled modelling approaches as hydrodynamic and ecosystem coupled modelling (Merino et al., 2012) and coupled physical–biogeochemical modelling (Blanchard et al., 2012). The FISHRENT model (Salz et al., 2011) combine bio-economic simulation and optimisation modelling in a multi- fleet, multispecies model to simulate values of biological and economic variables in order to evaluate management strategies and the consequences of different policy decisions. The model generates basic economic indicators like gross value added, net profits, together with specific outputs such as the size of stocks and fleets, production, costs, catches and landings.

Models can assess the risks and vulnerabilities of specific fish populations to climate change yet adaptive measures are context specific and require a case by case approach. Adaptive management schemes can subsequently ensure sustainable fishing practice, such as by limiting catches based on changes in recruitment, growth, survival and reproductive success (Shelton, 2014). As such, fish population dynamics models can help identify and assess suitable context-specific adaptation options and monitor their effectiveness over time.

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1.3 Water management and droughts

Over the past couple of decades, the frequency and magnitude of concurrent climate extremes such as heat and drought events have increased and caused great damages (IPCC, 2021). Vulnerability to and potential consequences of heat and drought impacts are continuously increasing (Niggli et al., 2022). According to Forzieri et al., 2018, **all regions of Europe are projected to experience a progressive increase** in multi-hazard losses, but a noticeable pattern is the strong increase in damage load in southern Europe in the coming decades, with the most southerly regions progressively more prominently affected by future climate extremes than the rest of Europe. A large part of the north-south damage gradient relates to droughts, which will **strongly intensify in southern parts of Europe** and become less severe in northern regions. Significant increases in the severity of concurrent heat and drought extremes have been observed between 1951 and 2016 in North and South America, Europe, Africa, Asia and Australia (Hao et al., 2018). Between 2011 and 2020, 55% of the European regions have had extreme-to-exceptional summer drought (van Daalen et al., 2022). Furthermore, there is evidence that concurrent **heat and drought events will become more frequent in the future** (Wu et al., 2021; Mukherjee et al., 2022). In assessing floods impacts, Lincke et al. (2018), also consider risks for Alpine glaciers, as **glacier melting** and retreat with warmer temperatures are exacerbated by ice-albedo feedback patterns. The analysis finds that under all RCPs, there is a projected reduction of about 50% of the glacier volume over the Alps by the 2050s, and much higher reductions later in the century, especially under high warming scenarios. These will have economic costs from the decline in summer river flows, affecting water availability, hydropower, river transport and stability (landslide risk), as well as the loss of ecosystem services from Alpine species and habitats.

Sutanto et al., 2019 underline how drought plays a substantial role in the occurrence of the **compound and cascading events** of dry hazards, especially in southern Europe as it drives duration of cascading events. In particular, fire is placed at the top ranks as the most occurring last hazard in a cascading event, since fires are frequently categorised as an associated hazard to drought and heatwave. This leads to a combination of drought, and **drought-fire**, as the most frequent cascading pattern of dry hazards in Europe (5.9%). Moreover, some research supports the argument that drought may accelerate a **heatwave** and not vice versa (Sutanto et al., 2019). High temperature accelerates soil drying and in turn warms the atmosphere by gaining less water from evaporation (Miralles et al., 2018; Teuling., 2018). Increase in the atmospheric demand for evaporation exacerbates high temperatures leading to a heatwave and rising temperatures when droughts become more severe (Miralles et al., 2014; Rasmijn et al., 2010).

Few studies systematically analysed the **impacts of past concurrent heat and drought events** and their interconnectedness and cascading effects at the societal level in order to better inform future risk management and adaptation. Niggli et al., 2022, assessed that the sectors most affected by direct impacts of historical heat and drought extremes in Europe are the health sector and the agriculture and food production sector. In addition, the energy sector, the transport and mobility sector as well as the economy and financial system are also strongly affected if indirect effects that emerge from cascading impacts are also taken into account.

PESETA IV (Cammalleri et al., 2020; Feyen et al., 2020) assess annual economic losses nowadays around 9.4 €billion/year for EU+UK, with the most affected regions being Spain (1.5 € billion/y), Italy (1.4 €

billion/y), and France (1.2 € billion/y). Projected **drought losses** for 2050 for a 1.5 and 2°C warming scenario are estimated between 12.4 and 15.5€ billion/y respectively. Compared to the baseline (1981-2010) this results in an increase of drought damages of 37 and 70% for 1.5 and 2°C warming scenarios. Total economic losses from drought in Europe would grow up to 45 €billion/year with 3°C global warming in 2100. The strongest increase in absolute drought losses is projected for southern and partially western Europe. Drought conditions will become less extreme in Boreal and Continental Europe. Under the climate change mitigation scenarios, the damage in 2100 would be approximately halved compared to no mitigation and limiting temperature increase to 1.5°C can reduce the impact to 25€ billion/y. Drought-related losses are estimated to be the highest for the agriculture, public water supply and energy sector (Cammalleri et al., 2020). Depending on the region, between 39% and 60% of the total losses relate to agriculture and between 22% to 48% to the energy sector, while public water supply accounts for 9/20% of the total damage (Feyen et al., 2020). The impacts in the shipping transport sector are limited compared to the other sectors but could have relevant regional effects. Infrastructures could increasingly be impacted by damages from drought-induced soil subsidence. Heat and drought extreme events can impact single sectors as well as multiple sectors, and some sectors can be affected by several extreme events. At the same time, impacts in one sector can also propagate and affect other sectors, putting strain not only on one sector but on the whole system (Niggli et al., 2022).

Accounting for cross-border European Union's vulnerability to climate change, Ercin et al., 2021, assess the impact of drought risk for 2030, 2050, 2085 and for RCP 2.6 and 6.0 climate scenarios. Results show that Global climate change will make the EU's agri-food economy highly vulnerable to **drought in non-EU countries** in the future. The total amount of agricultural imports by the EU will be 25–35% more vulnerable to drought in the future compared to the current situation mainly because of change in drought severity, increased intensity, and duration of drought events, in the production locations of the imported products. Under the current climate around 93% of the agricultural imports to the EU come from locations with a low/low-medium drought severity. The rest (7%) are categorised as medium-high and high. This alters significantly under climate change, in 2050 under the RCP 6.0 concentration pathway, only 18% of the EU's agricultural imports come from locations with low drought severity and around 44% of the imports come from areas that will experience high and extremely high drought severity.

The analysis of **response and adaptation measures** to heat and drought extremes reveals the increasing complexity of system interconnections. Niggli et al., 2022, found that the direct and indirect impacts of heat and drought extremes led to manyfold responses and adaptation measures, which expands the possible connections and interlinkages that can emerge between the sectors. Some of the most impacted and impacting sectors were also those in which most response and adaptation measures were taken, namely the health sector, the agriculture and food production sector, the water resources sector and the transport and mobility sector. Mazzoleni et al., 2021, developed a system-dynamics model that considers mutual interactions between reservoir, drought, flood, and population systems under different water-management strategies, allowing to capture macroscopic trends in observed reservoir volume, population, per-capita water demand, and populations affected by floods. Results also confirmed the importance of **coupling the flood and drought systems in the modelling framework**. Although water-management strategies aimed at mitigating floods can alter reservoir volume, drought awareness and drought-management strategies can differently affect flood awareness and consequent losses. These results confirm how drought water-management strategies can in turn shape the severity of flooding and consequent losses. Supply-demand cycle and reservoir effect can emerge when increasing the maximum value of reservoir capacity. Because of the trust in the water-supply system and low drought awareness, an increase in affected population is found with exploitation strategy after a severe drought period, indicating the emergence of a reservoir effect.

Key gaps

The literature on drought impacts and relative costs for Europe seems to be well developed and does not show major gaps. We nonetheless underline the increasing need to incorporate drought compound and cascading effects and their cross-sectoral and cross-national implications in future macroeconomic impact assessment at global and EU level. A better coverage on **adaptation costs and possible EU strategies** is needed.

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2. River and coastal flooding (including extreme weather events and critical infrastructures)

Flood-related phenomena are among the costliest natural disasters in Europe (Leiter et al. 2009; EEA, 2017). Their impact has steadily increased in recent decades due to increasing population and built-up areas (Alfieri et al. 2018, Paprotny et al. 2018). While the taxonomy of flooding can count a high level of definition depending on the type of impact and climate variable (Kron et al. 2019), the main division is between river flooding, induced by the magnitude and frequency precipitation events, and coastal flooding due to climate-induced sea level rise (Bosello et al. 2012, Hinkel et al. 2014, Bosello et al. 2020).

Flood events produce both direct damages on infrastructures and population and indirect losses on the economic activities (business interruption, supply chain disruption) spilling over sectors with macroeconomic impacts affecting regional and national economic systems. Indirect impacts can be a significant share of the total losses (Carrera et al. 2015), or even double the direct damage (Koks et al. 2015, Dottori et al. 2018). Indirect losses are more difficult to be captured, especially in future projections scenarios also considering that sectoral and regional economic interdependencies need to be accounted for (Koks et al. 2019).

While coastal flood events will affect specific areas the most, sea-level rise is one of the major drivers of macroeconomic impacts from climate change (Bosello et al. 2020). On the contrary, river flood events are very unevenly distributed (Lincke et al. 2018), leading to future macroeconomic impacts that range from minimal to substantial in their extent (Ward et al. 2018). That future macroeconomic impact is often expressed in terms of damage and number of people exposed (Feyen et al., 2020).

2.1 River flood impacts

Overall exposure to floods has declined in most European countries, especially in central and northern Europe, nonetheless relative exposure (% of impact on GDP) has increased in several western and southern European states including France, Germany, Italy and the Netherlands. In Southern Europe, flash floods constituted the majority of flood events in recent years, while in Central and Western Europe, river floods are the most frequent event (Paprotny et al. 2018).

According to projections river flood risk in Europe could boom due both to global warming and continued development in flood-prone areas (Dottori et al., 2023). In 21 out of 37 European countries, the frequency of extreme events can more than double by 2035, and increase further afterward (Alfieri et al. 2015). Flood events are very unevenly distributed. Models consistently predict a relevant increase in future flood impacts in most countries in Western and Central Europe, (Rojas et al. 2013, Alfieri et al. 2018, Dottori et al. 2018), while in Southern European countries drought associated with heavy single-event rainfall and flash floods will be more common (Alfieri et al 2015).

According to Alfieri et al. (2018) population affected by riverine floods can rise from 350.000 pp/year for the baseline, to 650.000 (+86%) for specific warming levels (SWLs) of +1.5°C, to 674.000 (+93%) for +2°C, to 781.000 (+123%) for 3°C.

Economic impacts of river flooding

During 1980-2009 , above 80 percent of European economic losses caused by natural disasters were related to hydrometeorological events (EEA, 2010). Hydrological events (i.e., floods and wetland mass movements) accounted for 25 percent of the total climate-induced losses in the member states. The European Environment Agency (EEA) estimated 455 billion euros of damages during 1980-2009 (in 2015 values) (EEA, 2010), while losses for the period 1990/2016 have been estimated around 210 billion euros (Paprotny et al. 2018). Between 1963 and 2017 , flooding generated losses equal 0.08 / 0.09% of GDP. According to Dottori et al., (2023) by the end of this century, direct economic impacts from flooding are projected to increase for almost all EU countries moving from the currently estimated €5.6-11.2 billion to €30-61 billion in a 3°C warming scenario. Eastern European countries will be most severely affected with damages larger than 0,5% of GDP . Analysis at the country level also shows high damages in the United Kingdom, France, Italy, Romania, Hungary and Czech Republic (Paprotny et al. 2018).

Similar conclusions are derived by Lincke et al. 2018 (COACCH D2.3). The GLOFRIS model estimates that expected annual damage is steadily rising over the period 2010-2080 for the EU as a whole. In 2010, expected annual damage is €9.5 billion, which increases to between €71-80 billion in 2080 for most assessed RCP-SSP scenario combinations, while under RCP8.5-SSP5 this estimate is projected to rise as high as €255 billion. The difference across the scenarios is relatively small for 2030. The average EAD across NUTS2 regions for RCP4.5-SSP2 is €64 million, whereas this is €82 million for RCP8.5-SSP5. In 2050, The projected average EAD across regions under RCP4.5-SSP2 is €123 million, while for RCP8.5-SSP5 the average EAD across NUTS2 regions is €252 million. In this case differences between high- and low-risk regions become highly significant (the lowest observed EAD is €43,000 and the highest is €3.6 billion). Damages to road infrastructures are a tiny percent of the total, (annual €825 million in RCP 8.5 in 2080), but demonstrate a 165% increase compared to current climate.

Koks et al. (2019) account for the indirect effects of river flooding in Europe. The results demonstrate that they are particularly relevant for the activity of commercial services (+980%) and public utilities (+580%), compared to 2010. Increases in economic flood losses (up to 350%) can be expected for all global warming scenarios, but indirect losses rise by +65% if compared to direct asset damages, due to the increasing size of future flood events. Results show that flooding can have widespread economic effects across Europe.

Bosello et al. (2020) suggest that indirect impacts from riverine floods in 2070, can erode roughly 2.5% of GDP in the EU. Indirect, second-order effects are highly influenced by assumptions on the economic connections across countries and regions. For instance, assuming more frictions in interregional investment mobility, macroeconomic losses are smaller in magnitude. In this case, higher impacts are found under the SSP3 scenario, with a median loss in all the EU area of roughly 1.2% of regional GDP in the high impact case.

Adaptation: costs and effectiveness

Dams and reservoirs are the river and flash flood control measures most widely used in Europe. Dottori et al., 2023 appraise the potential of four key adaptation strategies to reduce river flood risk across Europe based on flood risk modelling and cost–benefit analysis (the analysis does not cover coastal, pluvial and flash flooding). Results show that the cost-effectiveness of all adaptation measures increases with the level of global warming in most of Europe. Avoided damages are projected to grow faster than implementation costs, driven by increased flood frequency and exposure. At the same time, with adaptation we can maintain flood impacts to present-day levels even for high levels of warming. Reducing flood peaks using detention areas is the most cost effective strategy (400% of net benefit). In a scenario without climate mitigation (3 °C global warming), they can lower projected flood losses in Europe by 2100 from €44(30–61) billion to €8.1(5.5–10.7) billion per year and lower population exposed by 84% (75–90%), maintaining a risk level comparable to today. The economic investment required over 2020–2100 would provide a return of €4(3.5–6.3) for each €1 invested. In this context, nature-based solutions are gaining momentum as flood adaptation strategy. Despite the absence of comprehensive economic evidence, recent studies by Le Coent et al. (2021) and Vogelsang (2023) reveal that these solutions are as cost-effective as or even more so than traditional grey adaptation measures for equivalent risk levels. Furthermore, the cost-effectiveness of nature-based solutions tends to increase over time, with suggested maturation periods of up to nine years, making them the preferred investment choice. However, uncertainty still surrounds the evidence regarding the extent of avoided damage mitigation achieved by these nature-based solutions.

BOX 2A. Models and Methods

River flow models can be broadly categorised into two groups: hydrologic and hydrodynamic models; both models have been extensively used for assessing the impacts of climate change on flood hazard at different spatial scales. Hydrologic models are commonly designed to simulate hydrologic processes occurring in watershed systems, such as rainfall-runoff, river flows, infiltration rates and groundwater recharge over extended time periods, ranging from months to years. Hydrodynamic models, on the other hand, are suitable for simulating the floodplain inundation process, such as flood extension, water depth, and flow velocity, and are essential instruments for supporting the decision-making of adaptation strategies in areas that are exposed to flooding (Ebrey R. et al., 2021). Model assumptions vary based on model type, mathematical assumptions, processes considered, and model technique. The LISFLOOD (Alfieri et al., 2016a, 2016b) and LISFLOOD-FP models have been used as a research tool within the pre-operational European Flood Alert System (EFAS) at the EU Joint Research Centre, and are used in many research together with GLOFRIS (Ward et al., 2016; Winsemius et al., 2017). HYPE (Lindstöm et al. 2010) and the Pan-European E-HYPE model (high-resolution application of the HYPE model), is a hydrological model developed for both small-scale and large-scale assessments of water resources and quality. Economic damages are often calculated by combining climate variables and multiple datasets with damage functions, GDP projections, and land use maps, within integrated models as OSDaMage (van Ginkel et al, 2020), and evaluating both socio-economic and climate scenarios projections.

2.2 Coastal flooding

Lincke et al. 2018 (COACCH D2.3) assess impacts on infrastructure, built environment, and transport due to coastal flooding as a consequence of sea-level rise for 2015 to 2100 for EU 28 countries and for most relevant scenario combinations, accounting for a global coastal mean-sea-level rises between 32 cm and 75 cm until 2100. Cumulated land loss (caused by both erosion and submergence) in the EU until 2100 ranges from 130 km² (RCP2.6 with adaptation) to 6,600 km² (RCP8.5 high end sea-level rise without adaptation), thus forcing, respectively, 0.1 to 21.5 million people to migrate (cumulatively over the period). 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, from 4.7 million (RCP2.6) to 9.6 million (RCP8.5) by the 2080s, if there is no investment in adaptation. Under an extreme "high-end" sea-level rise scenario featuring a global coastal average sea-level rise of 170cm by 2100, 30 million people are expected to be flooded each year. Arctic sea ice loss, along with other impacts of sea- level rise such as erosion, would have potential impacts from changes in extreme cold conditions, and possible windstorms, with potentially important economic costs for Europe.

Economic impacts of coastal flooding

Lincke et al. 2018 (COACCH D2.3), estimate that without further adaptation, under RCP 8.5 high-end sea-level rise of +1.7m, EU28 direct annual sea flooding costs could reach about €13 trillion in 2100. Under RCP 8.5 medium sea-level rise (between +32 cm and +75 cm) costs are about €4.5 trillion. Under a low-end sea level rise, respective values are €23-64 billion under RCP 4.5 and €22-58 billion under RCP 2.6.

According to Vousdoukas et al.(2020) annual direct damages from coastal flooding under current level of coastal protection will grow up to € 239 bn (0.52% of the GDP) for EU+UK in 2100 under a high emissions scenario (RCP 8.5) and € 111 bn (0.24% GDP) under a moderate mitigation scenario (RCP 4.5). For the mid-century € 10.9 billion and € 14.1 billion of direct losses were estimated in RCP4.5 and RCP8.5 respectively. In 2100 the highest absolute increase in coastal flood impacts without adaptation are estimated in France, the UK, Italy, and Denmark. For some countries, coastal flood losses could amount to a considerable proportion of GDP, especially under the RCP 8.5 for 2100, e.g. in Cyprus (4.9%), Greece (3.2%), Denmark (2.5%), Ireland (1.8%) and Croatia (1.8%).

Schinko et al. (2020) estimated annual expected sea-flood cost in Germany between $ 3.6 (RCP2.6) and $ 5.3 (RCP 4.5) bn , in France between $3.2 and $5 bn USD and in Italy between $1.4 and $2.4 bn in 2050. Coastal protection is particularly cost effective. Losses in Germany drop to $ 1.1 (RCP 2.6) and $ 1.4 (RCP 4.5) bn per year in 2050, in France to $ 1.2 to $1.6 and in Italy to $ 1 to 1.6 bn . The yearly protection costs are $ 0.28 to $ 0.37 bn for Germany, $ 0.32 to $ 0.36 for France and $ 0.1 to $0.13 bn for Italy.

The higher order economic implications of sea level rise can be huge and spread to landlocked areas (Bosello et al. 2020). In the high-end sea-level rise case, in 2050, some regions (such as Latvia, Malta, Veneto, Tuscany and Marche in Italy) can experience a regional GDP loss beyond or close to 2.5% also in a moderate warming scenario . In 2070 damages increase, with the majority of EU regions demonstrating losses larger than 2, 2.5% of their regional GDP.

BOX 2B. Sea-level rise-induced Soil erosion

Coastal erosion is a particular case of climate- change-induced soil erosion. Beach retreat can lead to more exceptional coastal flooding and cause its consequences to reach levels of scale greater than would have been caused by flooding in isolation. These factors are likely to change over time, as are their interactions, which are increasingly complex and uncertain but cannot be neglected in the development of coastal flood projections (Toimil et al., 2023). Shoreline change projections can be used to estimate the associated land loss due to storm events and long-term processes such as Sea Level Rise under different climate projections. The database EC-Joint Research Centre (2019) includes global estimates of SLR retreat for sandy coasts. It also includes estimates for storm retreat and a so-called "ambient change" which indicates shoreline change from factors other than climate change. Parametric models can be used to estimate coastal erosion at a regional level, by using a finite set of parameters to predict future data. These types of models often manage discrete values and estimate storm-induced erosion using two different approaches. The first one estimates erosion based on storm conditions and beach characteristics. The second approach predicts the beach profile response depending on wave breaking and water level variations due to storm surge (European Commission, Ebrey R. et al., 2021). Toimil et al. (2023) present a methodology for modelling the effect of short- and long-term erosion on coastal flooding, by coupling coastal flood projections with shoreline changes. This allows to quantify the effects of neglecting the coupling of flooding and erosion on future projections, including longshore sediment transport and storm-driven erosion. Results show that, in assessing future flooded areas, the contribution of storm erosion is important, but as moving forward in time and for higher radiative forcing scenarios, its effect is outweighed by longshore transport-driven long-term erosion and the effect of sea-level rise.

Adaptation: costs and effectiveness

Studies on sea-level-rise generally evaluate adaptation costs in terms of dike upgrade and maintenance[5], and beach nourishment. In particular, coastal protection seems to offer high benefit to cost ratios (Lincke et al., 2018; Bosello et al., 2020) even though the literature shows that implementation costs are largely variable due to the type of measure adopted (Dottori et al., 2023). Lincke et al., 2018 for instance estimates that 90% of the global coastal population and 95% of the global coastal assets are located in areas that have positive benefit to cost ratios for coastal protection regardless of the sea-level rise scenario.

Vousdoukas et al. (2020), estimate adaptation's costs and effectiveness to sea level rise in Europe. They assume hard measures (dykes) are raised to a level of protection that maximises their economic benefit (avoided flooding) relative to their cost. With adaptation the annual damages are reduced from 239 to 23 bn € for low mitigation and from 111 to 12 bn € for moderate mitigation in 2100. The estimated average annual cost of adaptation for the EU and UK over the period 2020-2100 is 1.9 bn €/year in the high emissions scenario and 1.3 bn €/year in the mitigation scenario. The highest adaptation costs are estimated for France (217-314 €million/year), Germany (145-243 €million/year), Italy (137-189 €million/year), and Denmark (145-243 €million/year). Lincke et al. 2018 (COACCH D2.3) estimates the EU27+GBR protection cost of 100 bn € (RCP2.6) to 200 bn € (RCP 8.5 high end) for the period 2071-2100.

Bosello et al. (2020) suggest that incremental adaptation to sea level rise determines an expenditure much smaller than the avoided damage, thus being highly cost/effective. Direct impacts and adaptation costs are computed for a "no additional adaptation scenario", assuming constant protection at 1995 levels and for a "with adaptation scenario", where the demand for safety increases with increasing affluence and higher dikes are built with rising sea-levels. The costs of coastal protection include construction and annual maintenance

[5] Maintenance costs can often represent the bigger proportion. They also generate a steady cost flow, even if sea-level would stop rising.

costs. In all the SSP-RCP scenario combinations, and in all EU regions, GDP costs in the presence of incremental coastal protection are significantly lower than without additional adaptation, showing that adaptation removes most effects of sea-level rise even with low investment mobility.

Kelly and Molina (2022) offer indirect evidence of the effectiveness of adaptation in the US market. They identify significant gains in property values with an increase in price of about 10% after five years from completion, for properties adjacent or inside areas where adaptation projects have been implemented. This suggests net benefit from adaptation and its cost effectiveness in mitigating climate change impacts associated with coastal flooding in particular.

BOX 2C: Models and Methods

Coastal hazard models estimate the magnitude and geographical extent of different coastal hazards such as coastal flooding and erosion, both for the current climate, and future conditions induced by anthropogenic climate change. When modelling and assessing adaptation options to reduce coastal hazards and impacts, there are several methods that can be used, depending on the scale and type of hazard analysed (Ebrey R. et al., 2021). To assess coastal flood hazard, a static inundation approach, also known as "bathtub fill", is normally used. This method assumes that all continental land lying below a certain water level (mean seal level) will flood if the area is hydraulically connected to the sea (Paprotny et al., 2018). Such models are usually refined taking into account land use based water-level attenuation (Vafeidis et al., 2019). Sea level rise (SLR) projections can be easily incorporated by increasing water levels. All models rely on bathymetry and/or topography data. Sources can be global or locally derived datasets, such as Digital Elevation Models (DEMs), digital population datasets and digital land use datasets.

Assessments of the future flood hazard are commonly performed by coupling atmospheric climate projections with land-surface schemes and hydrological models (Alfieri et al. 2015). The EAD is often calculated by taking the integral of the probabilities where protection standards are exceeded, multiplied by the damage that a certain exceedance level causes (Lincke et al., 2018). Other coastal management tools which provide a greater focus on ecosystem disruption often estimate the impact of hazards in the natural environment to identify climate change adaptation options for nature and ecosystems.

To account for the indirect impacts of coastal hazards, methodologies have been proposed to include indicators such as household displacement, financial recovery of households and businesses, business supply chain disruption, ecosystem recovery, risk to life and utility and transport disruption (Ebrey R. et al., 2021).

BOX 2D: Compound effect from multiple hazards on Critical Infrastructures

According to Forzieri et al. (2018) the current EAD of €3.4 billion per year affecting EU critical infrastructure is projected to increase to approximately €9.3 billion (€5.2–14.2), €19.6 billion (€12.5–34.0 billion) and €37.0 billion (€21.3–53.2 billion) per year by the 2020s, 2050s, and 2080s, respectively, as a result of the effects of climate change. Presently, 44% of damage is related to river floods and 27% to windstorms. However, by the end of the century, drought and heat waves will account for nearly 90% of climate hazard damage.

All regions of Europe are projected to experience a progressive increase in multi-hazard losses. Nonetheless, the damage from climate conditions by the end of this century will absorb less than 1% of annual investments in Northern Europe, but a much higher share in the Southern EU (e.g. 2.79% in Italy, 4.32% in Spain up to 5.21% in Croatia).

River and coastal floods will remain the most critical hazard in many floodplains and coastal stretches of western, central, and eastern Europe. Part of the coastal flood damage is likely to be reflected in the inland flood and windstorm damage. All infrastructures from ports, transportation, industrial machinery, and equipment will be affected. Although flood and windstorm damage is on the rise, its contribution will be quickly outweighed by those of droughts and heatwaves in the coming decades. Against this background, the degradation of water quality and the reduction of the decomposition rate of water and waste management systems, with corresponding higher costs for water and its treatment, are particularly concerning for the potential social consequences.

Climate model projections suggest only small changes in wind hazard. Therefore, economic impacts due to windstorms are quite stable for different warming levels. Windstorm annual losses are projected to reach € 7 bn/year for 1.5 and 2°C global warming by 2050.

Estimates of adaptation costs to make infrastructures resilient to climate up to 2040 indicate for EU+UK, an expenditure of €25 billion, plus a yearly maintenance of nearly €2 billion. The investments for adaptation required to face changes in climate up to 2070 would increase to €87 billion, with annual operation and maintenance costs of €3.4 billion. To make infrastructure climate resilient up to the end of the century, capital costs could exceed €200 billion plus €5.4 bn/y of maintenance costs (Alfieri et al 2018). These numbers suggest that infrastructure projects with a long life span may require a substantial additional upfront investment to ensure life-long resilience to climate hazards. Adaptation costs will not fall equally across Europe. Countries in southern Europe that will be exposed to higher risk levels could potentially have to direct a significant proportion of their investments in fixed capital to abating the future impacts from climate hazards on critical infrastructures.

Key gaps of flooding studies

Key improvement in river flood impact models:

- Statistical analysis and modelling of future flood trends often reveals great uncertainty and significant differences in models' projections due to the natural variability of extreme events and the difficulty to predict future trends.

- A key gap within river flood models often pertains to the quality and quantity of the available data. Hydrologic and hydrodynamic models usually require large observational datasets in order to adequately calibrate and validate the model, as water level changes during a period of hours and/or days during a specific flood event. This information is rarely available from Earth observations.

- A further key gap of flow models pertains to their spatial resolution. Ideally, these models should target the utilisation of unstructured grids, as those provide a more flexible connection between the upscaling and downscaling of model parameters to the underlying topography (Ebrei et al., 2021).

- Temporal dimension needs to be better evaluated. When applied to support decision-making flow and river flow models need to be capable of providing estimates of historic and current states of the hydrologic cycle and under different climate conditions.

- Hydrological models also need to be robust while flexible enough to be coupled with other families of models, such as for the simulation of the interactions of the hydrologic cycle with the earth and human-economic system.

- Most hydrologic models do not consider the effects of a coevolution human-water system, but only consider human impacts as an external force on the natural hydrologic cycle.

- While coastal adaptation has been quite widely assessed, few studies systematically analyse impact and costs of different riverine adaptation measures and future projections.

Key improvement of coastal flood impact models:

- Exposure to coastal flooding is often represented by simplified land-use classes, especially in analyses on a broader scale (continental or global). This leads to an underrepresentation of heterogeneities in exposure. Including assets with higher resolution, such as offered by Open Street Maps, is needed.

- In assessing future coastal flood impacts, an integrated, multi-hazard assessment mechanism is necessary to couple the impact of sea-level rise, longshore sediment transport and coastal erosion.

Better understanding of impact on critical assets and infrastructure:

- High resolution exposure data is required. While the spatial and temporal resolution of Global Climate Models (GCMs) has increased the confidence of climatic projections, providing greater accuracy in simulations of extreme events (Ebrey R. et al., 2021), the resolution of GCMs and even Regional Climate

Models (RCMs) (10-30 km) is generally too coarse to usefully support several adaptation assessments, bringing to inability to capture a large number of "local" adaptation assessments (Reder et al., 2020). While this issue is addressed by applying downscaling techniques and bias corrections, uncertainty remains large in these methods.

- Understanding of long-term climate risks is often limited by the lack of in-depth knowledge on the historical impacts of climate hazards, also due to the absence of harmonised loss data recording.

-Vulnerability does not usually account for different degrees of interconnectivity, technological heterogeneity, and the life span of infrastructures, which may influence susceptibility to climate extremes.

- A key challenge for further research in this area lies in the quantification of vulnerabilities of various types of infrastructures/sectors to the different climate hazards (Láng-Ritter et al., 2022).

- While the effect of existing structures is considered in the hydrological models, the building of new structures as a possible adaptation measure is not always considered, thus constituting a source of model uncertainty.

Multiple hazards interconnections need to be better assessed:

- Accounting for multiple hazards reinforce and overlapping (spatially and temporally) is needed. This influences the overall hazard level and the vulnerability of elements at risk through possible hazard interrelations or cascade effects.

- The availability of observational relations linking variations in multi-hazard impacts on vulnerability is often scarce, preventing a reliable integration of such effects in large-scale predictive systems.

- Future efforts should aim at also integrating systems designed for pluvial floods and storm surges (in coastal areas) and testing them on a variety of past compound floods.

- When accounting for extreme events such as windstorms and hail, few recent data and relevant research projects are present.

Better understanding of adaptation measures for both river and coastal floods:

- Local adaptation measures to reduce flood risks need to be better assessed and implemented into models.

- When accounting for adaptation costs, it is important to note that adaptation measures are very diverse and usually take place at the local level, with diverse regulatory, legal, and governance settings.

- Local-scale information on adaptation measures is not available at pan-European level.

- More research is needed for the accurate estimation of risk reduction measures and the effect of human behaviour in future risk estimation. Agent based modelling can help to understand human decisions based on the risk that they are exposed to, and therefore better estimates can be obtained to improve cost-benefit analyses for decision-making.

- More empirical data are needed to validate vulnerability models for adaptation studies, and disaggregated loss and damage data at finer scales shall be provided. Overall, more information is needed on the cost benefit/cost effectiveness analysis of adaptation, being one of the main criticalities in this area represented by the local nature of adaptation.

It is important to note that when it comes to flood impact assessment only rarely cost estimates at household dimension are present, while in most cases analyses containing aggregate GDP-level data are provided.

Non-monetary impact estimates on ecosystems and possible ecosystem services are often missing.

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3. Energy

The energy sector is heavily affected by climatic stressors, with temperature being one of the major drivers of energy demand, influencing summer cooling and winter heating behaviour of households and firms (van Ruijven et al. 2019). Future climatic conditions will increase the demand for energy required for cooling (Colelli et al 2023), while demand for heating might decrease due to warmer weather and fewer low-temperature extremes (Rhode et al. 2021). Cooling is predominantly powered by electricity, while heating uses a wider mix of energy sources. This, combined with changes in economic growth and population distribution, will change the fuel mix used by the different economic sectors and households. With the progressing electrification and integration of renewable energy sources, mostly solar and wind, weather-dependency of the European energy system has been increasing.

The impacts of climate change on **the demand side** are reviewed in the section on adaptation because adjustments in the use of energy consumption and in the adoption of energy appliances are considered a form of autonomous adaptation put in place by households or firms in reaction to experienced or expected changes in perceived temperature. Colelli et al (2023), though, develop a methodology that could be used to distinguish and assess the interactions between energy demand impacts from unexpected weather shocks - i.e. reactive adaptation stemming from short-term adjustments with fixed capital stock levels - and adaptation to long-term climate changes - i.e. proactive adaptation stemming from long-term adjustments in the capital stock. Future short-term adjustments from reactive adaptation will depend in turn on the long-term set of capital stock as well as on the number of unexpected extreme temperature events: the study shows that the compounding of shifts in the climate and weather anomalies increase the maximum annual peak load in Europe by roughly +20 GW (mostly in Italy, +8 GW, and Spain +6 GW), suggesting non-negligible impacts on electricity transmission and supply (Colelli et al, 2023).

On the supply side, climate change will affect **renewable energy resources** that depend on climate, such as hydropower generation, wind power generation, and solar power. Studies of **hydropower** on a global scale typically show both positive and negative climate change impacts in different regions, leading to a small, aggregated decrease in potential. Seasonal variability and uncertainty in climate change impacts on hydropower generation have been reported on various regions and magnitudes of impacts on individual plants level relative to the regional and global level (Yalew at al., 2020). For Europe, most studies show a **positive effect for northern Europe and a negative effect for South and Eastern Europe** (Hamududu & Killingtveit, 2012; Mideksa and Kalbekken, 2010; Van Vliet et al., 2016; Teotónio et al., 2017; Turner et al., 2017, Despres and Adamovic, 2020). Overall, **the uncertainty about European regional differences seems important across different studies.** The extent to which climate change affects hydropower in Europe differs among the studies from almost no effect (Zhou et al., 2018; Hamududu & Killingtveit, 2012) to decreases of 5-10% by the end of the century or before (Turner et al., 2017). Schleypen et al. (2019) suggest that in Europe, under a moderate scenario RCP4.5, the highest impact in 2050 will be in Finland, Estonia, and Serbia, while in 2070 Slovenia, Croatia, and Austria will suffer the highest declines in hydropower generation due to future climate change. Similar results are found by Gernaat et al. (2021), showing climate-change-induced decline in hydropower generation in Central Europe. Despres and Adamovic (2020) find that climate-scenarios are another important driver of uncertainty: while the median impact on hydropower production is expected to be small and positive in the total EU (0.9% with 1.5°C global warming (median value); 2.3% and 3.2% with 2 and 3°C warming), the Interquartile Range of hydropower generation impacts is 7% to 17% in northern EU countries and -10% to 5% in southern EU countries under RCP 4.5. The replacement of other energy sources with the additional hydropower leads to annual economic benefits in northern Europe of around 1.3 €billion (2015 values) with 3°C warming. On the other hand, the reduction in **hydro and nuclear production in southern Europe, especially in summer, is associated with higher** utilisation of thermal power units, increasing generation costs of around 0.9 €billion per year (2015 values) with 3°C warming (static power system of 2020).

Changes in wind patterns as a consequence of climate change can affect **wind power generation** through increased variability in generation, damages to wind turbines due to extreme weather events, intermittency in generation leading to increased firm backup capacity, and icing on wind turbines (Schleypen et al., 2019). Results are highly uncertain and characterised by strong seasonality (Moemken et al. 2018). Wind power decreases are reported particularly for southern Europe, while slight increases in wind power are projected for central and northern Europe (Carvalho et al., 2017; Yalew et al., 2020). Overall, climate change impacts on wind power generation in Europe seem to lead to reduced energy output in the future (Weber et al., 2018), but with consistent regional differences (Schleypen et al., 2019). In COACCH D2.4 Schleypen et al. (2019) show that the **wind load factor capacity** over Europe is maximised at 10.1 m/s, beyond which energy generation declines. Under RCP4.5, load factor capacity from wind power will decline by 5.6% by 2050 compared to the reference period of 1986-2005, while by 2070 the reduction will be 7.3%. Under RCP8.5, load factor capacity is projected to decline by 6.9% by 2050, while by 2070 the declines are projected to be 9.7%. Under this climate change scenario, the highest declines in wind power generation will be in eastern and western Sweden, and in Andalusia, Spain. Partially different results are found by other studies: Gernaat et al., 2021 suggest that Central Europe gains around +10% in wind energy production, while Despres and Adamovic (2020) project increases of up to 5% in Central and Southern Europe, while smaller impacts in other European regions.

Solar power may be affected because increasing temperature may lead to lower efficiencies for photovoltaic systems but higher for concentrated solar power (CSP) technology. The direct climate impacts of increasing temperature on solar power seems overall to be small (around 5%), yet robust. These effects are small because irradiation changes are small and the negative effects of warming occur mostly at higher latitudes, which already have lower PV potential than low-latitude regions (Gernaat et al., 2021). Similar results are found by Despres and Adamovic (2020).

Climate change is expected to reduce **cooling-based thermal power capacity**, such as nuclear and fossil fuel power plants, through reduced streamflow, warming ambient and streamflow temperatures. Global assessments of the vulnerability of the current freshwater-cooled thermoelectric plants project that more than

80% of plants in the US and EU will show some reduction in usable capacity by 2060 (Yalew at al., 2020 Van Vliet et al., 2012). Because higher water temperatures can lead to cooling problems for thermal power production, **power stations might require relocation or the addition of more cooling towers**, which could lead to **additional cost**. In particular, thermoelectric power plants in southern and southeastern Europe (Van Vliet et al., 2012). Coffel et al., (2021) show that climate change to date has **increased average thermal power plant curtailment** in nuclear, coal, oil, and natural gas fired plants by 0.75–1 percentage points, and project that each degree Celsius of additional warming may increase global curtailment by 0.8–1.2 percentage points during peak demand, requiring an additional 18–27 GW of capacity, or 40–60 additional average-sized power plants, to offset this global power loss. According to Despres and Adamovic (2020), total nuclear production would decrease in the EU by 0.5% with 1.5°C warming and by 1.8% in a 3°C warming static scenario.

The impacts on energy supply have also been analysed in the context of the multiple climate risks to **critical infrastructures** (Forzieri et al. 2018). The largest rise in damage for the energy sector relates to energy production − fossil fuel, nuclear, and renewable − as a result of its sensitivity to droughts and heatwaves and the **decrease in cooling system efficiency of power plants** due to higher water/air temperature. By the end of this century, droughts and heat damage are projected to account for 67% and 27%, respectively, of all hazard impacts on the energy sector in Europe (currently, droughts account for 31% and heat to 9% of the total impacts). Other hazards primarily impact energy transport systems, and an increasing body of empirical evidence highlights the vulnerability of the power system grid to extreme weather (Bartos et al., 2015; Bartos et al., 2016; Tobin et al., 2018).

Adaptation: costs and effectiveness

The impact of climatic stressors on **energy demand** have been rather extensively researched (De Cian and Sue Wing, 2017; De Cian et al., 2013; Howell and Rogner, 2014; Schaeffer, 2012; Bazilian et al., 2011), with a major focus on the **residential sector** (Yalew at al., 2020). Future climatic conditions are likely to have non-homogeneous impacts on energy demand. While energy demand for heating is expected to decrease not only due to the increase in average temperature level but also due to energy renovations and new energy efficient construction (Mastrucci et al., 2021), demand for **cooling services** will increase (Colelli et al. 2023, van Ruijven et al 2019, De Cian and Sue Wing, 2017). These responses are largely autonomous and can therefore be considered both as an impact or an adaptation. Responses can be divided between the intensive margin, which is the short-run change in energy demand for a given level of capital stock; the extensive margin, which is the long-run change that can also include changes in the number and efficiency of energy-using appliances. Colelli and Sue Wing (In. prep.) show that the estimated effects due to climatic variation are greater than the ones due to weather anomalies, and that impacts obtained from a single metric that disregards the difference between climatic and unexpected weather exposure underestimates the future energy demand for adaptation. The study shows that the extensive margin response of electricity for cooling affects all sectors: with the residential accounting for around 45%, services and industry accounting for around 25% and agriculture for the remaining 5% of the total aggregated demand response, respectively. On the other hand, the long-run response of fossil fuel demand for heating is mostly driven by the residential sector, and by a minor share by industry. Results from Mastrucci et al. (2021) show that the energy demand for **space heating is projected to decrease** substantially (up to 70%) under SSP1 scenario, and more slowly in SSP2-3, as a result of energy renovations and new energy efficient construction. Colelli and Sue Wing (In. prep.) show that, in Europe, total demand combining all fuels and sectors declines by 3.5 EJ/year in 2050 under RCP 4.5, due to the strong reduction in building fossil fuel use from lower HDDs. The study finds that energy demand variations in 2050 under RCP 4.5 exhibit a strong regional gradient: while Northern European states see a reduction in annual residential fossil fuel demand of around -40% and small reductions in electricity demand in residential and commercial buildings due to lower electric heating, Southern European states experience a growth in residential annual electricity demand of around 20% and reductions in annual fossil fuel demand of residential and commercial buildings ranging from -10% to -20%. Furthermore, Colelli and Sue Wing (In. prep.) underscore that if future intensive use of appliances due to unexpected weather anomalies is accounted for in the climate change impact projections, the change of electricity demand in Southern Europe and of fossil fuel demand in Northern Europe could double with respect to the mean climate impact, in the worst case scenario.

Tröltzsch et al. (2018) underline that there are many studies that provide **autonomous adaptation costs** for changes on energy demand, assessing the **decline in electricity demand for Europe** as a whole, but with **increases in Southern Europe** (De Cian and Sue Wing, 2017; Wenz et al., 2017, van Ruijven et al 2019) due to increasing temperature in summer. Colelli et al. (2023) show that in 2050, hotter daily maximum temperatures in conjunction with higher AC ownership synergistically increase the amplitude of daily peak load for cooling, with shocks being particularly large in Southern regions where daily summer peak demands increases by 20–30% (an additional 10 and 13 GW in Spain and Italy). Schleypen et al. (2019) also highlights how the impact of future climate change on energy demand in Europe will be heterogeneous across NUTS-2 regions. Vrontisi et al. (2021) estimated the change of energy demand for European islands especially due to increased cooling demand and desalination (linked to heatwaves and low precipitation). **Desalination** could result in an average increase of electricity demand by +10% (with ranges across islands from 1% to 40%). Focusing on household AC specifically, Colelli et al. (2023) assess that end-use efficiency improvements could facilitate reductions in heat exposure with smaller increases in electricity consumption. Improving European AC units' seasonal energy efficiency ratios (SEERs) from their current region-specific average levels to their best available levels could moderate annual electricity consumption increases by 50% (17 TWh).

Economic costs of climate change impacts on energy

The **macro-economic assessment** of climate change impacts on **wind power and hydropower supply** (Bosello et al. 2020) points at a moderate reduction in GDP all over the EU regions, reaching a maximum decline in the Madrid region of roughly 0.6% in 2070 in the SSP2-RCP6.0 scenario combination (GDP impacts are similar under both the assumption of high or lower mobility of investment). Under RCP8.5 scenario, losses are concentrated in those EU areas where hydro power, and renewables in general, are more intensively used (i.e., northern EU countries or alpine regions). Negative GDP impacts in many regions can be larger in more moderate climate change scenarios, like RCP 4.5 or even 2.6, because of the higher use of renewable energy.

Macro-economic assessments of climate change impacts on **energy demand** (Standardi et al. 2023) show that the increasing cooling needs represent an increase in the production costs for firms particularly felt in Southern European regions (Spain, Italy Greece, Cyprus, Malta but also Romania and Bulgaria). In 2070, in RCPs 8.5 and 6.0 but also in RCP 4.5 if associated with SSP3, these cost increases could induce macroeconomic losses larger than 1% of GDP in some regions of the southern EU with a peak of -7.5% in Cyprus and potential losses in the order of 2% of GDP already in 2030. The macroeconomic effects for the residential sector are more difficult to track, as they trigger mostly a re-composition of households' demand across the different items they are consuming (increases in electricity and declines in oil and gas). Regarding regional differences, economic patterns of winners and losers between Northern and Southern Europe are found. Contrasting scenario combinations, the authors find that mitigation reduces adverse macroeconomic effects for Europe up to a factor of ten in 2070, from 0.4% GDP loss in SSP5-RCP8.5 to 0.04% in SSP2-RCP2.6. Another result pertains to the tensions between adaptation and mitigation is the potential increase in the carbon price (between 5 and 30% in 2100) needed to meet a given temperature goal once the energy demand needs for adaptation are taken into account (Colelli et al. 2022).

While **investments** increase in order to meet higher electricity demand, higher prices can bring GDP or welfare losses. In Europe, for example, between now and 2050, under current climate policies, an additional €235 billion of investments and operational expenses in power generation and transmission are needed to provide the additional electricity needed for cooling (Colelli et al. 2022). The additional supply-side costs will be passed on to consumers through **increases in the price of electricity** around 2%-6% due to the adaptation-energy feedback in different regions. Ambitious mitigation policies can cut by more than half the increase in the costs of the energy system induced by adaptation, depending on the stringency of the climate target.GEM-E3 model results indicate that the impact of climate change on electricity demand can bring average **cumulative GDP losses** over the 2040-2100 period equal to 0.6% of the baseline in the RCP2.6 scenario and 1.2% in the RCP8.5 scenario.

Diurnal peak demand requirements can often be met by solar photovoltaic (PV). However, in cases where renewable sources alone cannot fulfil these power needs, power systems must rely on the rapid scaling up of flexible generation technologies, typically involving gas and coal-fired generation. When facing unanticipated weather shocks, power system operators may face **additional costs** in the form of **balancing services**, **load reduction measures**, or, in the worst-case scenario, **unexpected power outages**. The additional costs that climate change may pose due to such remedial actions are currently unaccounted for in the existing literature.

Key gaps

Key elements need to be better understood and included in future assessments:

- Technological progress in the energy sector, improved energy efficiency in end-use heating and cooling technologies, and technology adoption are often not explicitly modelled in demand and supply studies.

- Spatial resolution of energy demand and expenditure data are coarse with respect to that of climate data. Gridded data and downscaling approaches need to be further implemented.

- Supply side impacts need to be re-assessed by expanding the scope of the investigation in multiple domains: high frequency data; power-plant level data; market implications; role of adaptation.

- The economic assessment of the energy impacts of climate change should consider a broader set of cost metrics such as balancing costs and congestion management for transmission operators and change in energy prices. The assessments should include compound impacts on power systems due to contemporaneous demand and supply side shocks through energy system models (e.g. simulating power dispatch and capacity expansion need to be carried out).

- Extreme climatic events, which can impact on energy transmission and distribution and some energy generation technologies, including the impacts on energy transmission of coastal flooded infrastructures require more research.

- A consistent gap is related to relevant links to food, water, biodiversity (for example, regarding large-scale ramp-up of bioenergy or hydropower), sea-level rise and its effect on coastal energy infrastructure, permafrost thawing and its impacts on oil and gas resource availability.

- Adaptation policy options need to be monitored over time and across countries, and more systematically assessed and included in modelling exercises.

- Geopolitical changes and future macroeconomic and international relations-related implications of non-EU countries on the European energy sector need to be better understood, and so do the geopolitical implications of reducing demand substantially due to reduced heating needs and increased supply from indigenous renewable sources.

Relevant improvements from a modelling perspective:

- Technological progress in the energy sector, improved energy efficiency in end-use technologies, and technology adoption are often not accounted for in macroeconomic analyses.

- Households' behavioural changes vary across income groups and over time, and such heterogeneity has not been well represented in macroeconomic analyses.

- There is limited inclusion of supply-side impacts in IAMs.

- In assessing energy scenarios, most of the IAMs models still need to integrate climate-energy feedback into their assessments. As a consequence, we sometimes lack a comprehensive understanding of how an increase in the energy needs for adapting to climate change might affect the economy, the energy systems, and the environment.

- The use of diverse assessment methodologies in the energy sector studies often limits the comparability of climate change effects across different studies. It is important to study the energy sector in an inter-sectoral approach, which will require modelling energy sector impacts at the same spatial scale as other impacts.

BOX 3. Models and Methods

The literature on modelling climate change impacts on the energy sector includes two broad approaches: studies examining the physical, direct impacts on a specific energy carrier, generation technology or specific energy sector or side of the market (demand or supply); and studies that couple the output of such physical models with energy system models, Integrated Assessment Models (IAMs), or Computable General Equilibrium models (CGE). These models can trace the general equilibrium effects of energy shocks on other sectors through the changes induced by final prices and factor remunerations. They can evaluate how energy impacts affect the energy transition and the costs of mitigation policies.

Econometric or statistical approach have been mostly applied to analyse the direct impacts on energy demand (Schleypen et al., 2019; De Cian and Sue Wing, 2017), while most of the studies on energy supply impacts have applied model simulation approaches (Schleypen et al.,2019). Physical impacts on the energy supply are then incorporated into IAMs or CGEs as variation in the resource stock that is used to generate energy (such as water availability). Climate change-induced variations in energy demand are mainly captured using two different modelling approaches: (i) energy for heating and cooling is endogenously captured by incorporating the number of heating (HDD) and cooling degree days (CDD) into the demand functions for heat and/or electricity; and (ii) changes in overall energy demand are exogenously captured by incorporating long term elasticity in relation to temperature into the demand function for the relevant energy uses (European Commission, Ebrey et al., 2021). Empirically, econometric estimates can be derived analysing per capita demand for different final energy carriers associated with heating and cooling (electricity, petroleum products, and natural gas) as a function of per capita gross domestic product (GDP) and exposure to hot and cold days (De Cian and Sue Wing, 2017). Changes in overall energy demand can also account for long term elasticity in relation to temperature into the demand function for the relevant energy uses (European Commission, Ebrey et al., 2021).

Dispatch and capacity expansion models are useful tools to evaluate the compound impacts on the power systems occurring when demand-side shocks (eg. peaks in electricity demand) co-occur with supply-side impacts (eg. impacts on the electrical grid and on power plant operations). These models simulate the operations of a power system with high spatiotemporal detail, and therefore require the availability of high-frequency projections of demand and supply side impacts of climate change.

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4. Tourism

The tourism industry is a vital part of the EU's economy. In 2019, the last year before the COVID-19 pandemic heavily hit the tourism sector, the gross value added directly generated by tourism amounted to an estimated €572 billion, or 5% of the total gross value added in the EU (Eurostat, 2023). The overall demand for tourism is expected to increase over the next few decades, however its distribution, timing, and type will probably shift as a result of climate change. The impact of climate change on tourism is conveyed either by its direct effects, such as increasing temperature, or by its secondary effects, such as rising sea levels (Rosselló-Nadal, 2014; Schleypen et al., 2019). Today the peak of mass summer tourism in Europe is mainly focused on the Mediterranean. However, increasing temperatures, heat waves and limited water availability may all negatively affect this destination and lead to a shift towards the more comfortable climate of the midseason (i.e. Autumn and Spring) or of northern regions (Tröltzsch et al., 2018). Furthermore, coastline retreat and sea level rise may reduce beach coverage and coastal recreation affecting tourism infrastructure and assets on the coasts (Nicholls et al., 2011; Enríquez et al., 2017). By a similar token, winter tourism will be severely affected by changes in snow availability, cloudiness and wind speed that will impact the length and quality of the season, the economic viability of resorts at lower altitudes, increase adaptation costs, change the choice of destination and timing of visits (Prettenthaler et al., 2015; Perrels et al., 2015, Tröltzsch et al., 2018).

Schleypen et al., (2019), analyse the effect of climate change on **summer tourism** for 29 European countries. They identify an inverted U-shape relation linking temperature and tourism demand. In the case of average monthly temperature, the turning-point is a few degrees Celsius beyond sample temperature average. They thus conclude that the effect of increasing average temperature can rapidly turn to be negative and steeply declining in the whole area. The effect of maximum temperature is also negative beyond 35°C. This makes it reasonable to expect larger decreases in tourism flows in countries located in Southern Europe where max temperatures are already at 30°C. Clearly, in colder countries the increase in temperature can be beneficial to the sector. This also suggests the possibility of strong geographical redistribution of tourism flows. The study has also analysed the influence of weather extremes on the duration of visits. It appears that some of the extreme indices have a significant negative effect on the amount of holiday nights.

A particularly climate-sensitive segment is **winter tourism.** European Alps are projected to experience a strong decrease in snow cover duration and depth (Willibald, 2021; Steiger and Abegg, 2013). By 2050, the impacts of climate change will be so severe that their effect will dominate the normal vulnerability of the ski industry to climate variability also in the presence of artificial snowmaking. According to the OECD (Abegg et al. 2007), in the early 2000s for 91% of today's alpine areas, the presence of natural snow (without artificial snowmaking) could be considered certain. With an average increase of +1 °C, now approaching, this value would drop to 75%. With +2 °C, certainty would affect only 61% of the resorts, with +4 °C, only 30%.

Economic impacts on tourism sector

The SOCLIMPACT project analyses climate impacts on tourism for European islands due to sea level rise and heatwaves. The work shows that touristic expenditures can drop quite substantially, with an average of -13.4% (with ranges across islands from -7.2% to -25.1%) in the RCP2.6 climatic scenario and an average of -22.3% (with ranges across islands from -12.3% to -41.1%) in the RCP8.5 scenario compared to a baseline scenario (no climate change). This has damaging effects on the islandic economies, especially for the tourism-dependent islands. The GEM-E3 model estimated cumulative GDP losses over the 2040-2100 period could be on average 1.2% in the RCP2.6 scenario and 3.2% in the RCP8.5 scenario due to less tourism arrivals. For Balearic islands and Crete, with high GDP-share of tourism, GDP losses could ramp up to 6.9% (Vrontisi et al. 2021).

Adaptation: costs and effectiveness

The challenges to adaptation in the tourism sector can affect both 'supply' and 'demand' (Tröltzsch et al., 2018; ToPDAd, 2015). On the demand side this includes changes and volatility of demand, on the supply side, challenges are both technological (e.g. snow making, heating/cooling systems) and behavioural (e.g. operational practices, and diversification of activities). Few cost estimates of adaptation measures exist, and most are in relation to technological adaptations, especially for artificial snow-making.

As tourism is a highly subsidised economic sector, public funding at all levels will need to take into account the sector's needs to develop its resiliency and sustainability, including investments in infrastructure (Tröltzsch et al., 2018).

Key gaps

In general, this sector appears to be **poorly analysed** from almost every point of view, especially given the major importance of tourism for many European economies.

- The literature **on physical impact indicators** is inconsistent and a consensus regarding the correct approaches to apply to each destination is yet to be firmly established. This is particularly an issue for **snow reliability.**

- To the best of our knowledge, there are few **recent economic estimations** on climate impacts on tourism in Europe, both from demand and supply sides.

- **Very little data is provided for winter tourism**, and more effort must be also put on heat-related and wildfire impacts, especially for summer tourism.

- A possible level of analysis could **account for ecosystem losses, sea level rise and losses of wildlife**.

- Very few recent studies are published on **adaptation strategies and costs**.

- There is the need to reinforce future tourists' preferences and understanding through use of widespread surveys to determine tourists' attitudes towards specific climate features, as well as different tourism activities.The evidence on this is still limited to a few local studies.

Some modelling improvements need to be implemented:

- **Demand models** have solely relied on temperature as climate-related drivers, mainly due to multi-collinearity issues among climate variables, and there are still only a few studies incorporating composite tourist climate comfort indexes into demand models.

- Studies incorporating tourism into IAM's/economic models need to enrich the **adaptation options** considered, particularly on the supply side.

BOX 4. Models and Methods

In order to study the impacts of climate change on **tourism,** there are different methods used in the literature[6]. A large number of papers studies this impact by using quantitative methods, while a relatively limited part of the literature addresses the issue by using surveys and qualitative approaches (Steiger et al., 2017).

Quantitative evaluation of climate change effects on tourism consist of three main categories: i) Evaluation through physical changes of factors that can be impacted by climate change (i.e., snow availability); ii) Tourism climate indexes (designed to identify comfortable climate condition ranges for tourism activities); and iii) Demand models (as discrete choice modelling, time series analysis and aggregate tourism models). Climate change impacts on the tourism sectors and results from demand models can also be included within an economic or Integrated Assessment Model (IAM) to assess implications of impacts and adaptation options on the economy/environment system (European Commission, Ebrey et al., 2021).

Applying econometric methods, quantitative methods mostly use climate indices and tourism demand models to investigate the impact of climate change on tourism demand. Schleypen et al., 2019, in the COACCH Deliverable D2.4, analyse the effect of climate change on summer tourism demand for 29 European countries, applying quantitative econometric analyses and using both monthly and annual country-level data from EUROSTAT. The study focuses on the effect of temperature and climate extremity on the number of arrivals and nights spent, by analysing the effect of present temperature and extremes and a one-year lag of these variables to examine the effect of past experience (2000-2016). While monthly data are used to specifically analyse the effect on tourism in Europe during summer months (June to September), the annual data allow to analyse the aggregate effect during the entire year. In order to examine different patterns in visiting different countries, the effect of temperature on tourism was analysed for five regions in Europe, differing in climate and income. Apart from the number of arrivals and number of nights spent by tourists, a number of establishments and bed places are provided at NUTS 2 level. Besides tourism data, the econometric model relies on socioeconomic data, including GDP and Population density.

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5. Business, industry, trade, and supply chains

Direct biophysical climate change impacts on business and industry, are most likely to affect organisations located in areas at risk of extremes (such as floods or heatwaves), or those whose activities are closely linked with climate-sensitive resources (such as agricultural and forest product industries, food, paper and energy industries, tourism) (Tröltzsch et al., 2018 and see in detail sections 2.3).

A particular category of impacts on business is that conveyed by **trade channels** and the **supply chain**. Climate change impacts, such as droughts or floods, can have spillover effects that cross borders and continents propagating very far from the location of their initial occurrence (Carter et al., 2021, Knaepen, 2023). For instance, the literature suggests that temperature and natural disasters can have a negative effect on exports in low income countries (Jones & Olken, 2010; Gassebner et al., 2010; Oh & Reuveny; 2010). They also tend to increase imports in developing countries. These effects are strongly influenced by the degree of financial integration of economies and tend to be highly industry-specific (Oh, 2017; EL-Hadri et al., 2018).

Because the large share of raw materials and intermediate goods imported from climate-sensitive countries and the significant share of final goods exported, the European industry will be importantly affected by trade and supply chain transmitted climate shocks (Burke et al. 2015; IMF 2017; EEA, 2017; Schleypen et al., 2019 Bosello et al., 2020; Hildén et al. 2020; West et al. 2021). At the same time, trade can also be a climate change impact dampener as it offers an economic system the possibility to retrieve abroad goods and services impaired at home or destine abroad goods and services not absorbed by an impaired domestic demand (Schleypen et al., 2019; Carter at al., 2021).

Hristov et al. (2020), for instance, show that international trade effects may in fact lead to EU export increases in wheat, barley, grain maize and soybean notwithstanding declining yields (see section 1) Schewzicz et al. (2020) also shows that negative spillover effects from agricultural losses outside the EU are significant in comparison to the economic losses from the internal EU climate changes. They can completely erode potential gains from higher yields in the Northern EU.

Schleypen et al., 2019, provides empirical evidence of the effect of supply chain disruption caused by natural disasters in Europe. Results highlight a potential average reduction in the value of annual export over the century by around 11% compared to the baseline in the RCP 2.6 and 13 % in RCP 4.5 scenario. This negative effect is mainly driven by dynamics in the manufacturing and agricultural sectors.

Another category of impacts affecting businesses are that on the **labour force**. Many studies typically identify a bell-shaped relation across climate variables, (usually temperature) and labour productivity. The average annual temperature level at which value added begins to decline are comparatively lower for the industry and construction than services but highly differentiated across sectors and regions within the same country (Schleypen et al., 2019). Dasgupta et al., 2021 show that average annual temperature level turning point for **labour productivity** is higher in hotter regions, pointing at the potential role of some forms of adaptation or acclimatisation. Van Daalen et al. (2022) estimated that, in European high-heat- exposure sectors (agriculture, forestry, mining and quarrying, and construction) the observed increase in temperature has caused a 0.98% decline in the **number of working hours** in the period 2016-2019, compared with the reference period of 1965-1994. The largest declines in working hours are found in the Southern EU while Northern European countries may show slight increases in labour productivity (Dasgupta et al., 2021). In **future scenarios**, labour productivity in outdoor labour could decline by 10-15% by the end of the century compared to present-day in southern European countries and by 2-4% in northern EU areas according to Gosling et al., (2018). These trends are confirmed by ILO (2019) pointing to 0.03% **total working hours** loss in 2030 due to heat stress in Europe and Central Asia, with the possibility to more pessimistic outcomes where European **labour productivity** could decrease by around 0.3%, 0.8% and 1.6% in the 2020s, 2050s and 2080. Higher losses in the Southern EU are reported also by Szewczyk et al. (2021). At the sectoral level climate change will result in a decline of **labour productivity** by 4.3% in industry and by 6.6% by 2070 in the **construction sector in RCP8.5 by 2070 (**Schleypen et al., 2019). **Effective labour, understood as working hours and output during those working hours,** is expected to decrease in southern Europe by up to 13.6% under 1.5°C temperature increase (2030-2050), 18.2%s under 2.0°C of temperature increase (2050-2070) and 28.5% under 3.0°C temperature increase (2070-2090, Dasgupta et al. 2021).

Analysing the **food supply chain** Orlov et al. 2021, highlight that the impacts of heat stress on worker productivity could offset the economic benefit potentially induced by positive CO_2 fertilisation effect on crop yields in most regions, leading to substantial economic losses.

Several studies also investigated **indirect economic implications of the reduced productivity of workers**, usually assuming that impact functions are specific to economic sectors (Szewczyk et al., 2021), and considering different labour intensity for different sectors (Kjellstrom et al., 2018; Orlov et al., 2019, 2020). CGE-based analyses show that declines in labour productivity transmit through the overall economic activity and eventually affect the macroeconomic performance of the regions (Bosello et al. 2020). Southern and central-eastern European regions are hit more adversely showing potential GDP contractions in the order of 1.5-2%. Cooler areas like northern-Europe, but also Austria, or Italian Alpine regions, can gain roughly a 1% improvement in the economic performance. GDP changes are considerably lower, and less differentiated, than the initial impacts on labour productivity used as input data. This is a direct consequence of the smoothing action played by market mechanisms: on the one hand, less productive factors are substituted with other production factors; on the other hand, the demand partly readjusts towards the consumption of less labour-intensive goods and services becoming cheaper in relative terms.

Similar results are provided by (Szewczyk et al., 2021). The indirect annual economic losses in Europe could reach 1.15% of the EU GDP by the 2080s in the worst case scenario with very uneven regional distribution. Spain, Italy, Greece, Cyprus and Romania could lose around 2% of their GDP by 2080s, or 3%–5% under the worst-case scenario. Central European countries could lose 0.6% of their GDP (1.1% in the worst-case scenario) by the 2080s, while in northern Europe they would not exceed 0.23% GDP even in the worst-case. The distribution of losses reflect not only the varying degree of exposure to heat but also a different regional distribution of occupation types and of their physical intensity.

More recent research confirms that macro-economic losses can be substantial in Southern European regions, in most of the scenarios by 2070. In assessing the macro-economic effects of climate-induced impacts on labour productivity in the EU sub-national regions Standardi et al., 2023 find that regions within the same country can be affected quite differently, confirming previous results. This is evident for Italy, where Alpine regions may experience economic benefits while the rest of the country is badly impacted by global warming. In general, Southern Mediterranean and Eastern regions are more subject to macro-economic losses (bigger than -1% of GDP per year) while Scandinavian regions may experience some economic gains.

Box 5A. Focus on labour Productivity: terminology and overview

Labour supply is often defined as the amount of labour, measured in person-hours, offered for hire in a given time period (Dasgupta et al. 2021). Warming directly affects labour supply (working hours) by reducing the allocation of time to labour beyond certain thresholds, especially in weather-exposed sectors such as agriculture. Climate change might also reduce performance (labour productivity) during these working hours when workers are under severe heat stress. These two dimensions (supply and productivity) of labour can be combined into a single compound metric, which we call effective labour. This compound metric allowed us to estimate the effect of future climate change on both the number of hours worked and on the productivity of workers during their working hours.

Real labour productivity (based on hours worked)[7] for the total economy over a given time period *t* is calculated by dividing GDP by hours worked. At industry and regional level, GDP in the numerator is replaced by industry GVA, defined as output value at basic prices less intermediate consumption valued at purchasers' prices. Real labour productivity per person employed in the total economy for a given time period *t* is calculated by dividing GDP by employed persons. At industry and regional levels, GDP in the numerator is replaced by industry GVA. In both cases, for the total economy, GDP is used instead (Eurostat, 2021).

European industry is mainly driven by manufacturing, of which the regions with the largest average industrial GVA and above 50% share of manufacturing are the regions of Lombardia which includes Milan in Northwest Italy (ITC4), Île de France which includes Paris (FR10) and Auvergne-Rhône-Alpes (FR71), Stuttgart (DE11), Oberbayern (DE21), Düsseldorf (DEA1) in Germany, Catalonia in Spain (ES51) (Schleypen et al., 2019). Similar to the industry sector, the main contributing countries in the EU's average

[7] EUROSTAT'S LABOUR PRODUCTIVITY INDICATORS (LPIS) Methodological note and quality aspects

services sector GVA are Germany (19.7%), France (16.6%), the UK (16%, Italy (12.4%), and Spain (8.4%). The services sector is mainly driven by trade and transport, public administration, and finance subsectors.

Adaptation: costs and effectiveness

Part of the reason for European actors' inadequacy to respond to impacts related to cross **border spillover effects**, trade **channels** and the **supply chain**, is that policy processes on climate change impact, adaptation, and vulnerability provide responses to climate change impacts as a local challenge, mostly within national borders. Consequently, they often fail to capture and plan for interdependencies and cross-border climate impacts. As cascading climate risks spread across national and sub-national boundaries, climate change adaptation is thus being redefined as a global challenge that requires transnational and collaborative governance solutions (Knaepen et al., 2023; Persson, 2019), potentially requiring inclusive engagement with a wide range of actors across multiple countries and governance levels. Responses to cross-border climate impact may, however, have undesirable consequences, eventually resulting in trade disruptions and inflation in the global market (as in the case of export bans on agricultural commodities) (Knaepen et al., 2023).

At the national level, proactive measures, like **zoning** and **building standards**, could be implemented. **Public information campaigns** on disaster risk could incentivize private adaptation measures and insurance uptake. After a disaster has happened, financial disaster relief aid and solid financial institutions could speed up the disaster recovery period and decrease the length of the supply chain disruption. **Geographical diversification** in a company's production network could also serve as a means to adapt against supply chain shocks. Depending on the degree of spatial correlation of natural disaster shocks, companies need to balance the degree of regionalization in the supply chain. In case specific natural disasters are characterised by a high degree of spatial autocorrelation, more global diversification in the production network could be beneficial.

When accounting for **labour productivity losses** due to climate change, in order to protect industries that have developed in regions with comparative advantage (e.g., from abundance in natural resources, technological advantage, etc.), adaptation action needs to be strengthened in light of anticipated climate changes and corresponding estimated impacts. Few studies have attempted to model adaptation to heat stress (Szewczyk et al., 2021), often assuming labour-wide adjustment due to **endogenous work shifts** (Gosling et al,. 2018) or accounting for **air conditioning or mechanisation in agricultural and construction** (Orlov et al,. 2020). Autonomous adaptation for labour productivity through increased technological adaptation to heat stress (mechanisation and air conditioning) might reduce productivity losses up to 40%, for the lower warming levels (Szewczyk et al., 2021), and for labour intensive sectors such as agriculture (Orlov et al., 2021). Neither adaptation costs nor planned public adaptation are accounted for in these studies.

While climate change will affect all aspects of businesses, there has been a particular focus on **insurance**, because of its climate sensitivity and because it has a role in supporting adaptation to extreme events. Europe has an extremely complicated and variable insurance system, with very different models among Member States and thus the impacts of climate change are heterogeneous (Tröltzsch et al., 2018). The insurance sector, which offers protection against potential losses to assets and crops, is strongly being looked at for offering solutions for building resilience against extreme weather events in terms of providing financial cover and incentivizing climate risk reduction. Projected increase in the occurrence and intensity of extreme weather events will challenge national insurance systems and global reinsurance, which may lead to increases in insurance premiums and decreases in coverage.

Key gaps

Most studies look at labour productivity or aggregate GDP indicators, while direct and indirect impacts on businesses and value chains have not received much attention.

- With the exception of some particular case studies, **the direct impact on industry** from climate extremes appears to be underestimated. There are few studies that assess the direct impact of extreme single events on industry/services. Usually, impacts on those sectors are studied as decreased Labour Productivity (due to heat impact) or at macroeconomic level. Few recent estimations are provided on direct damages and increasing costs for industries in areas at risk of extremes (such as flood risks), or those whose activities are closely linked with climate-sensitive resources (with the exception of the productivity sectors analysed before in the review).

- Only a few **industrial sectors have been analysed**. Overall lack of granularity in providing industry-specific impact assessments.

- Studies tend not to include **adaptation costs and planned adaptation actions**

- The analysis of spatial **labour reallocation** would deserve a deeper investigation, as well as Increasing the sectoral detail of the econometric analysis.

- Apart from labour productivity, economic costs for **trade and supply chain disruptions have not been widely considered.**

Key gaps from modelling perspective:

- Accounting for the relation between climate change and **economic performance with adaptation**, macroeconomic assessments are often developed at a level of aggregation which is larger than that of the majority of adaptation measures (Ebrey et al., 2021). This, coupled with the lack of reliable information on adaptation costs and effectiveness, prevents a wider application of these approaches.

- A gap still remains between the aggregation level of adaptation cost estimates performed by IAMs and CGE models, and the more precise, but not generalizable, local dimension of adaptation solutions. CGE models can partly bridge the gap between aggregate-level climate change damage and adaptation functions, but lack the ability to capture discontinuity, irreversibility and non-market consequences typical of climate change impacts. Both IAMs and CGE models are mostly applied to the study of mitigation and much less of adaptation. Similar considerations apply also to econometric approaches.

- The ICES CGE modelling framework does not adequately capture the potential for significant disruptions outside the **equilibrium state** that may have important implications in terms of their cascading effects and policy responses. Such methods also assume **'rationality'** of responses whereas, it is often the unforeseen or irrational nature of human responses that is more concerning in times of crisis (CASCADES, 2022).

- Model outcomes need to be elaborated beyond the "macroaggregate" level GDP or productive output to capture disaggregate impacts on different 'groups' of actors that may affect particular communities or industries and/or may exacerbate inequalities.

- Much work is still required in the modelling of wider **indirect economic impacts with adaptation** (Ebrey et al., 2021), including cascading network effects using empirical data instead of stylized or reduced-form approaches.

BOX 5B. Models and Methods

Four distinct approaches can be easily identified in the literature of climate change **impacts on industry and via international trade** (Tröltzsch et al., 2018): (i) **qualitative assessments**, developed on national and company level; (ii) **indicator-based assessments**, usually build on past information of different indicators, single observations or time series ; (iii) **supply chain risk assessments**, usually built on multi-regional Input-Output (MRIO) or network analyses; and (iv) **macroeconomic assessments**, usually developed through CGE modelling approach.

To provide empirical evidence of the effect of disruptions in the **supply chain** in the propagation of shocks, Schleypen et al. 2019, construct a measure to capture the degree of input-output connectivity between sectors and countries. When accounting for climate change impacts on **labour productivity**, estimations for all RCPs are usually produced applying a fixed-effects panel regression method linking sectoral value added per working population to temperature, controlled for by including both the linear and its squared-term.

Data from COACCH D2.4 are then used by Bosello et al. 2020 to account for macroeconomic impact assessment on labour productivity, using the ICES macroeconomic model. Labour productivity impacts are implemented directly as changes in the productivity of the labour production factor in the agricultural and industrial sectors.

Accounting for **cross-border impact due to climate change**, Carter et al., 2021 provide a conceptual framework to describe and analyse cross-border climate impacts and their consequences. The framework focuses on how a climate impact occurring at a given location may be transmitted across borders, potentially presenting a risk to a region of interest that is remote from the initial impact, which may require a response from actors in that region. CASCADES (2022), underlines how models can provide important insights into the relative economic significance (including to the EU) of cross-border climate impacts. However, the conclusions they provide cannot be considered comprehensive because of the limitations and restrictions in scope they are subject to and because of the uncertainty related to cross-border climate impacts.

Accounting for disasters and the **insurance sector at the aggregate level in the EU**, 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.

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6. Health

The impact of a changing climate on human health is a widely studied topic and the mechanisms of transmission are many. Exposure to **prolonged and intense heat** in particular is one of the key risks that will affect the European population. The consequences of exposure to abnormal heat can have significant negative impacts on human health, ranging from discomfort due to extreme temperatures to potentially fatal outcomes (Gasparrini et al., 2015, Vicedo-Cabrera et al., 2021). Literature provides evidence on the direct impacts of exposure to heat extremes on **mortality** (Sheridan and Allen, 2018; Moghadamnia et al., 2017). Globally, 37% (range 20.5–76.3%) of warm-season heat-related deaths observed between 2000 and 2020 can be attributed to anthropogenic climate change (Vicedo-Cabrera et al. 2021), while warming observed during the same period has been associated with an average of 15 additional deaths per million inhabitants per decade in Europe. Portugal and Spain show the highest rate with an average increase of 30.6 annual deaths per million per decade in Spain (van Daalen et al., 2022). In the 2022 summer only, over 61000 deaths were attributed to extreme temperatures in Europe (Ballester et al., 2023). Significant associations have also been found between **rising temperatures** and i) hospital admissions due to psychiatric diseases (Ščasný et al., 2020), mental health issues (depression, bipolar disorder and schizophrenia) and suicide attempts (Thompson et al. 2018); ii) skin diseases (including skin cancer) and allergies (Bednar-Friedl et al., 2022); iii) respiratory, and infectious diseases (van Daalen et al., 2022); iv) cognitive performance (Piil et al., 2020), criminality and broader social conflicts (Zhu et al., 2023; Sanz-Barbero et al., 2018; Hsiang et al., 2013).

The magnitude and pattern of **future heat-related morbidity and mortality** will depend on warming levels and other important factors such as population growth and ageing, urbanisation trends, adaptation efforts, and development choices (Ebi et al. 2021). Without adaptation, an increased mortality from extreme heat for the EU is expected, up to 90,000 deaths per year by 2100 in a 3°C global warming scenario and 30,000 deaths annually for a 1.5°C global warming scenario (Naumann et al. 2020; Bednar-Friedl et al. 2022). More severe impacts are assessed by Ščasný et al. (2020), which estimate that for Europe in the RCP8.5 scenario, the annual mortality will possibly increase up to 300,000 excess deaths by the last quarter of the 21st century, accounting for exposures above the minimum mortality temperature (MMT)[8], including extremely

[8] The reference (or threshold) temperature when the average daily mortality at the population-level is minimum. Temperatures above the MMT (i.e., days classified as moderately to excessively hot, or heatwaves) are considered non-optimal , and pose an increased risk of death on susceptible population sub-groups.

hot temperatures (classified as heatwaves). The mortality rate is one-half as large under RCP4.5 (145,000 deaths) and about one-quarter for RCP2.6 (85,000 deaths). Their estimate for RCP4.5 is consistent with PESETA III projections (Forzieri et al., 2017). On a decadal timescale, the influence of heatwaves on mortality is estimated around 40-50% of the total heat burden (Albizuri et al., 2019), but this share is likely to increase appreciably in future warming climates.

Europe is particularly vulnerable because of the **age structure of its population (infants and the elderly are vulnerable groups), the prevalence of pre-existing diseases, pre-existing income and health infrastructure inequalities, as well as the degree of urbanisation** (van Daalen et al., 2022). Higher levels of temperature rise from global warming are generally expected for some Eastern and Southern European cities, and these temperature increases are exacerbated by the Urban Heat Island effect in highly urbanised areas. Even under RCP2.6 scenario, it is still the case that UE cities can experience warming above 2.5°C due to the UHI (Ščasný et al., 2020). Threshold temperatures that trigger an increase in heat-induced mortality vary across space and over time. A study for Spain (Díaz et al. 2015) suggests that threshold temperatures inducing an increase in heat-related mortality are generally higher in the South (40°C as opposed to 30°C in the North), while the effects of extreme temperatures have reduced over time, particularly in relation to mortality outcomes due to cardiovascular causes, which is a primary cause of death during heatwaves. Other studies show that, overall across Europe, winter benefits from reduced cold-related mortality more than compensates for higher heat-related mortality in summer (Ciscar et al., 2018; Szewczyk et al. 2020; Feyen et al., 2020). Relatively to the world average, larger **heat-related mortality risks** are observed **in the European region**, in particular, the Western and Central areas of the continent while smaller estimates were found in most locations in Asia and the Americas (Vicedo-Cabrera et al., 2021). Within Europe, the incidence of heat-related mortality and morbidity will be higher in SEU (Forzieri et al., 2017; Gasparrini et al., 2017; Guo et al., 2018; Díaz et al., 2019; Vicedo-Cabrera et al., 2021; Bednar-Friedl et al. 2022).

In the study of the effects of climate change on health, a major part of the literature has been concerned with investigating the effects of extreme heat. However, there are also other effects such as the increased occurrence of **vector-borne diseases**. In Europe, tick-transmitted Lyme disease is the most prevalent vector-borne infection (Erber and Schmitt, 2018), where an expansion of its range has been observed, accompanied by an increase in incidence in thirteen Western European countries (Ščasný et al., 2020). Lyme disease is expected to advance northwards and to higher altitudes, and to retract in southern European countries (Bednar-Friedl et al., 2022).

The presence of mosquitoes that act as vectors of transmission has also increased but is still not a major factor. This is the case of *Aedes* mosquitoes, which can transmit tropical diseases such as dengue, chikungunya and Zika (Romanello et al., 2022), or *Culex* mosquitoes, considered the main transmitter of West Nile virus (Colpitts et al., 2012). In the last decade, several hundreds of West Nile virus (WNV) cases have been reported in Europe (including over 2000 cases in 2018), not only in southern areas but also in central Europe (Semenza and Paz, 2021). Some evidence suggests that the likelihood of WNV transmission in several southern European countries around the Mediterranean axis will increase by 2025 and even more by 2050 as a consequence of climate change (Semenza et al., 2016). The distribution of *Aedes albopictus* is also expected to expand to most of Europe under climate change, while *Aedes aegyptus* will remain limited to certain coastal areas (Kamal et al., 2018).

Anopheles vectors, responsible for malaria transmission, are extremely sensitive to changes in climate. Projected changes in temperature and precipitation in Europe will result in a northward spread of the disease, and according to some, potential reductions in Mediterranean areas due to reduced precipitation (Hertig, 2019). However, other evidence points out an increase in malaria risk particularly in Southern and Southeastern European countries (Fischer et al., 2020). Nonetheless, the risk to human health is expected to remain low up to 2050 in Europe due to social, economic and healthcare contexts (Bednar-Friedl et al., 2022).

Extreme weather events, such as floods, droughts, wildfires and coastal inundation, can have direct and indirect impacts on people's health, ranging from death to mental health problems (Bell et al., 2018). According to the International Disaster Database (emdat.be), from 2000 to September 2023 extreme weather events[9] in Europe caused 3,685 casualties, more than 18,000 injured people and left almost 14 million people affected. The total damage exceeds 300 billion (adjusted) US$.

Indirect effects of these events include mental health issues, such as depression, anxiety, stress (Ebi and Bowen, 2016; Foudi et al., 2017; Mostafizur Rahman et al., 2023), and even evidence of post-traumatic stress disorder (PTSD) (Nasri et al., 2020). Dealing with insurance in the aftermath of the event has also been found to be an additional source of stress for flood victims (McKenzie et al., 2022).

Schmitt et al. (2016) conclude that the impact of extreme weather events on human health constitutes a major economic effect that is also likely to increase rapidly in the future unless adaptation measures are taken. Such events also have important distributional implications and are therefore becoming a major public health issue. Further work is needed to determine the range of costs associated with these impacts for the coming decades to 2050 and beyond under different climate scenarios.

Beyond the direct impacts of climate change (or before them), the continued burning of fossil fuels has already been related to 117000 deaths in 2020 from exposure to particulate matter of less than 2.5 µm in diameter (PM2·5) air pollution, with the transport sector being the main contributor (van Daalen et al., 2022). At +2.5°C, mortalities due to exposure to PM2.5 are projected to increase by up to 73% in Europe. At +2°C, annual premature mortalities due to exposure to near-surface ozone are projected to increase up to 11% in Western and Central Europe and Southern Europe (with a decrease of up to 9% in Northern Europe) (Bednar-Friedl et al. 2022). Overall, the potential health co-benefits of reduced air pollution due to mitigation policies alone range from 7% to 84% of mitigation costs in EU countries (based on nationally determined contributions) when exploring the additional benefits of a mitigation target of 2°C or 1·5°C (van Daalen et al., 2022; Markandya et al., 2018).

Economic health-related costs

While many studies look at **phisycal climate change impacts on health,** fewer studies specifically consider the direct costs for **individuals** (household level) and their well-being, and the implications in terms of costs for the health-care sector.

Value of a Statistical Life (VSL) estimates are used to monetize death-equivalent mortality rates (Carleton et al., 2022), and therefore also the benefits and costs of adaptation. Ščasný et al. (2020) quantified the VSL for heat-related fatal events through discrete choice stated preference surveys in Spain and the United Kingdom. VSL estimates were found to be very similar in both countries (€ 1.5 million in Spain and about € 1.6 million in the UK). Adjusting values for income in nominal Euro, the VSL for the heat wave context for the EU28 ranges between 2.33 million Euros (2015 values) and 2.15 million Euros.

By combining these values with the future mortality impacts of heatwaves in Europe, under a +3,4°C scenario (SRES A1B) the economic impacts reach 67 billion PPS[10] Euro in the 2020's, 214 billion PPS Euro in the 2050's, and 315 billion PPS Euro in the 2080's, starting at 6 billion PPS Euro in the baseline (Forzieri et al., 2017). This damage is distributed unevenly across European regions – 64% is attributable to premature deaths in Southern Europe (200 billion PPS Euro), while Central Europe and Western Europe experience about 15% of the damage. The economic impact of premature mortality was also estimated, ranging from 180 to 200 billion PPS Euros in the 2030's. These figures increase in 2050 to 285 - 390 billion PPS Euro for (RCP4.5 and RCP8.5, respectively). Under RCP4.5, the impacts remain at around 300 billion PPS Euro until the end of the century, raising up to 700 billion under RCP8.5 by 2100.

Some studies assess the impacts on **hospitalisation costs** at national level. Karlsson and Ziebarth (2018) assess the short and medium-term impact of extreme temperatures on population health and health-related costs in Germany. Under both approaches, they find that extreme heat significantly and immediately

[9] Events considered include storms, storm surges, floods and other weather events such as fires and droughts. However, as heat waves have been covered extensively in this section, they have been left out of the selection (CRED, 2023).

[10] The purchasing power standard (PPS) is the technical term used by Eurostat for the common currency in which national accounts aggregates are expressed when adjusted for price level differences using purchasing power parities (PPPs). Thus, PPPs can be interpreted as the exchange rate of the PPS against the euro.

increases **hospitalizations and death rates**. They find health-related economic costs in terms of mortality (including the harvesting effect[11]) and morbidity (hospitalisation costs and labour productivity loss) can reach €5 million for every 10 million population per hot day with maximum temperatures above 30 °C. The study by Adélaïde et al. (2022) estimated **excess visits to emergency rooms** and outpatient clinics and hospitalizations for heat-related causes using health indicators collected by the French national heatwave plan. They derived the related impacts in terms of total excess mortality and years of life loss, as well as the share of the population whose activity was restricted activity. They estimated the economic impact of heat waves between 2015 and 2019, to have reached €25.5 billion. The costs of excess mortality represented 90% of the total cost (€23.2 billion), and was calculated using VSL and VOLY estimates. The loss of well being was measured by looking at the WTP to avoid restricted activity days (€2.3 billion) and morbidity costs (€0.031 billion) were obtained considering direct medical costs, indirect costs (production loss), and intangible considerations via WTP. Covering both heat and cold stress, in terms of mortality, hospitalisation costs and productivity changes in Germany, Hübler et al. (2008) show that the reduction in cold stress only partially counteracts heat-related deaths and these could increase by a factor of 3.7 by 2070-2100 compared to current levels. By the same year, **hospitalisation costs** could reach 300 to 700 million euros (2015 value) per year, a 6-fold cost increase compared to current levels. Exposure to extreme heat can undermine people's capacity to work (van Daalen et al., 2022), both through the direct impacts on the health of workers and by reducing labour supply and productivity (Dasgupta et al., 2021), possibly affecting worker incomes (see Section 8). The resulting losses of labour output can affect the broad economy, and a stream of literature has quantified the **macroeconomic costs** in terms of GDP changes, and welfare changes due to heat impact on health (see Section 5).

The assessment of the economic costs of vector-borne diseases remains understudied. Mac et al. (2019) reviewed the literature on Lyme disease and found a handful of articles estimating its economic impact in several European countries, with annual economic costs ranging from 0.014 US$ per capita in Sweden, which represents 142,562 US$ when multiplied by the country's population (9.96 million), to 1.36 US$ in the Netherlands, reaching a total cost of 23.12 million US$ (population of 17.08 million). The highest value was obtained in the US, 2.41 US$ per capita (786 million US$).

Adaptation: costs and effectiveness

Some progress has been made in Europe's health adaptation. Van Daalen et al., (2022) reports that in 2021, 15 (68%) of 22 European countries reported having national health and climate change strategies or plans, and 10 (45%) reported conducting a climate change and health vulnerability and adaptation assessment. Many (150) European cities reported performing city-level climate assessments, with 118 reporting that climate change threatens their public health or health services. Despite the increasing risk posed by extremely high temperatures, only a few countries have set a maximum workplace temperature in national legislation. It varies between Member States from 28 to 36 degrees Celsius.

While the extent to which societies will globally be able to **adapt to climate change** is not well understood (Andrijevic et al., 2021), adaptation actions that might be taken by households to protect their assets related to the stock of human health and capital include changes in the **use of energy to ensure a comfortable environment and reliance on medicines and health services**. While studies assessing the impacts on health expenditure in Europe are not always available, recent studies show that adaptation measures such as heat alert systems can be very effective, though they do not completely reduce all heat-related impacts (Hunt et al., 2016; Sanderson et al., 2018). The adaptation measures against the health risk of heat and drought extreme events are mainly based on technological mechanisms, such as air-conditioning in private and public spaces, as well as institutional mechanisms, like monitoring and alerting actions or restrictions if needed (Niggli et al., 2022; Zuo et al., 2015). In order to respond to the health threat of heat waves, countries developed extreme-temperature prevention and alert plans that act as heat health warning systems. However, the most efficient way to alleviate the impacts of heat stress is probably to adjust indoor temperatures with the **use of a cooling device, such as a fan or an air conditioning (AC)** device, leading to an increase in

[11] A short period of excess mortality that is followed by a compensating period of mortality deficit (i.e., fewer deaths than expected, because those people have died at a younger age) is quite common, and is also known as "harvesting". Because of this, mortality deficit in a particular time period can be caused by deaths displaced to an earlier time.

energy demand. There is particular concern that the diffusion of air conditioning (AC) equipment throughout the developing world will amplify electricity demand responses to higher summer temperatures (De Cian and Wing, 2017, Randazzo et al., 2020). Some research has shown that in locations where the "summer" season lasts for most of the year, demand for cooling accounts for 50% or more of the total electricity demand (IEA, 2018). The study by Colelli and De Cian (2020) underlines that already by 2050 climate change will induce a median 30% (90%) percentage variation in a building's energy demand for cooling and a median −8% (−24%) percentage variation for heating, leading to a 2% (13%) increase when cooling and heating are combined, even under the RCP1.9. However, owning a cooling device is not only dependent on exposure to climatic conditions but also on socioeconomic factors, such as having enough income to be able to afford a cooling device, meaning that the overall impact of heat stress hinges on the ability to adapt to it (Andrijevic at al., 2021). While numerous studies exist on the assessment of climate change on energy demand (Van Ruijven et al., 2019), fewer explicitly focus on household energy expenditure (Randazzo et al., 2020) or household energy investments (De Cian et al. 2019). The study by De Cian et al. (2019) estimated the propensity of households to invest in air-conditioning and thermal insulation that can improve households' resilience to weather shocks. If households in hotter places in Europe have a lower probability of improving walls and roof insulation, exposure to a warmer climate raises the probability that a household adopts air conditioning. The impact of air-conditioning on electricity expenditure is quantified in (Randazzo, et al., 2020). Households who adapt to high temperatures through air-conditioning spend, on average, 35%–42% more on electricity compared to households who do not choose this solution.

Adaptation to heat, therefore, can represent an additional factor influencing the **energy poverty**[12] of households, a concept that in Europe has been traditionally related to expenditure for heating in winter times and will need to be extended to cooling in the summertime. Intensive (higher energy demand for cooling) and extensive (buying an AC appliance) margins are adopting measures that are constrained by households' disposable income. If household resources are not sufficient to adapt, the households experience the total burden of climate change impacts. When the households can choose to adapt, the additional expenditure usually implies a new arrangement of goods and services demand. The analysis by Campagnolo and De Cian (2022) combines a computable general equilibrium model with a downscaling module based on household survey data to evaluate the impacts of climate impacts and mitigation policies on households 'expenditure and energy poverty. Both mitigation policies and climate change impacts increase households' expenditure on electricity, whereas spending on other fuels is reduced. The net effect varies in sign depending on the region, but some places could experience an increase in electricity poverty. Air conditioning is unevenly distributed across income levels, making evident the existence of a disparity in access to cooling devices and showing that the use of AC is an income-dependent adaptation solution (Pavanello et al., 2021; Colelli and Mistry, 2022).

Andrijevic et al. (2021) take the ownership of AC as a proxy for adaptation action against heat stress, in order to estimate the future cooling gap, which represents the difference between the population exposed to heat stress and the population able to protect against heat stress with AC. Depending on the scenario of socioeconomic development, the total population affected by the cooling gap may vary between 2 billion and 5 billion people in 2050, with the scenario-dependent range widening further towards the end of the century. The analysis shows vast regional **inequalities in adaptive capacity** for heat stress, underscoring the need to account for the different potential levels of adaptation in the assessments of climate change impacts. It has been shown by Colelli et al. (2023) that AC adoption responds non-linearly to per capita income and cooling degree days (i.e. the annual sum of daily average temperature exceedances above the 24 °C threshold). Results suggest that Europe's current per capita income is already high enough to support the widespread adoption of AC, but moderate ambient temperatures have kept prevalence low. Accounting for income and population projections in 2050, the impacts of future temperature increases in Europe will increase AC prevalence as an adaptation solution to more than double, from 19 to 41%.

As we have seen, relying on air conditioning as the primary strategy for coping with extreme heat can lead to maladaptation, increased vulnerability, fuel poverty and other problems. There is some evidence of how a

[12] There are many different definitions and visions of energy poverty, but they all refer to a level of energy consumption that is insufficient to meet certain basic needs (González-Eguino, 2015). According to Reddy et al. 2000, energy poverty can be defined as "the absence of sufficient choice in accessing adequate, affordable, reliable, high-quality, safe and environmentally benign energy services to support economic and human development".

more holistic approach that addresses thermal comfort from an individual, building, urban and landscape perspective can help identify more sustainable alternatives (Jay et al., 2021).

Key Gaps

- The main health impacts of climate change are related to rising temperatures. Other areas, such as vector-borne diseases, represent a much smaller impact and remain understudied, but trends call for increased attention over the medium to long term.

- In the case of extreme temperatures, some gaps arise from a lack of comparable analysis of morbidity impacts, including mental health outcomes. Projections are needed on a comparable basis for such impacts, taking account of climate, demographic and economic changes in the coming decades.

- Projections of mortality and morbidity costs due to extreme heat in European countries should be refined to a more granular level for detailed welfare and budget impact assessments.

- Future research on climate change and mental health is needed, with a focus on confirming hypotheses about the weather's impact on severe psychiatric disorders exacerbations.

- A better assessment of health-related costs and impacts at households and national level is needed, especially if compared to data available for other impact types.

- Assessment of the needed supply of public health services to meet expected increases in health-treatment demand is crucial.

- Systematic evaluation of the effectiveness of early warning systems, increased air conditioning usage, and other adaptation options at a NUTS2 level is still necessary.

- Evaluation of adaptation effectiveness, considering differences in available resources at the household level, for different classes of households, requires further attention.

BOX 6. Models and methods

Quantitative methods are most commonly used to study the health impacts of extreme heat induced by climate change. On the one hand, epidemiological risk functions are used that relate the impact of temperature to excess mortality, starting from an optimum temperature where mortality is lowest (Honda et al., 2014). When valuing the economic effects of mortality, it is common to use the Value of a Statistical Life (VSL) and the Value of a Life Year (VoLY) (Adélaïde et al., 2022). The estimation of these deploys a range of methods which have as a basis the willingness to pay/willingness to accept an increase in the risk of death. However, valuing life in contexts of differing human development has important ethical and methodological implications. Romanello et al. (2022) suggest addressing this problem by presenting the cost of heat-attributable mortality as a proportion of GDP and average annual income equivalent in the countries concerned.

Climate change impacts on health can also be measured in terms of well-being loss. This is obtained from the use of VSL/VOLY as mentioned above. Direct impacts of such loss in money terms has been obtained through contingent valuation (questionnaire) methods, as well econometric approaches (OECD, 2012). An alternative to well-being loss estimation is the human-capital method which estimates loss of productivity. Other methods involving input–output and the computable general equilibrium (CGE) models are best for estimating the overall impacts, including indirect ones (Zhao et al., 2021).

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7. Biodiversity and ecosystems

Climate impacts on **natural systems** are projected to have important (economic) effects (Balmford et al., 2002). The IPCC's latest report on climate impacts, adaptation and vulnerability specifically highlights: biodiversity loss, ecosystem structure change, increased tree mortality, increased wildfire, and ecosystem carbon losses as being of important concern (Parmesan et al., 2022). At the same time, the ongoing decline of biodiversity poses its own challenges on the global economy, particular for economic sectors that are dependent on healthy and functioning ecosystems (Dasgupta, 2021). Joint workshops between IPCC and IPBES confirmed that solutions to addressing the twin challenges of climate change and biodiversity loss are often interlinked (H. O. Pörtner et al., 2021; H.-O. Pörtner et al., 2023). Because of these interlinkages it thus makes sense to consider them jointly also in the context of further climate change adaptation measures.

The specific impacts of climate change on biodiversity occur across multiple dimensions depending on whether ecosystems, species distributions or local populations are reasonably well understood. Changes in temperature and precipitation are expected to cause ecosystem dependent feedback that affect future carbon stocks, NPP and other aspects of ecosystem functioning (Krause et al., 2019; O'Connor et al., 2021). On the species level climate change is expected to "shuffle" many communities around as species expand their distribution (Antão et al., 2022; Pecl et al., 2017; Pigot et al., 2023; Trisos et al., 2020), or go locally extinct particularly so at northern latitudes or high altitudes (Antão et al., 2022; Chen et al., 2011). Average changes and climatic extremes are expected to further contribute towards declines in local species population persistence (Cornford et al., 2023; Spooner et al., 2018; Trisos et al., 2020). Given that the persistence of species populations and functioning ecosystems is associated with multiple ecosystem services (e.g. pollination, carbon storage, soil functioning) and climate adaptation options through Nature-based solutions, the drivers of biodiversity and climate change should be addressed in an integrated way (Díaz et al., 2019; H.-O. Pörtner et al., 2023), also in the context of maximising potential socio economic co-benefits with human society.

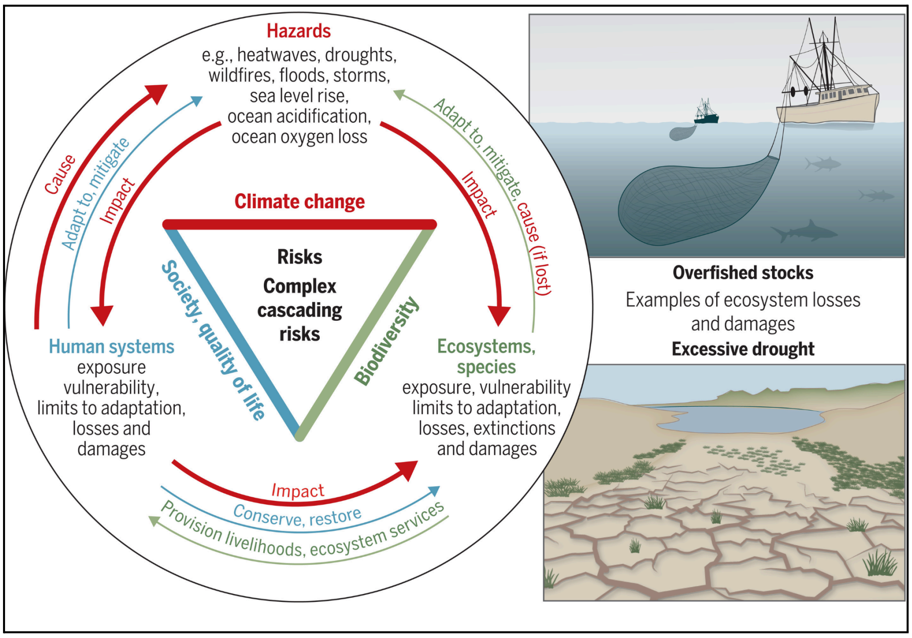

Figure 1| Dynamic interactions between climate, biodiversity, and human society. Source: Pörtner et al. (2023)

Economic impacts from changes to biodiversity and ecosystems

The specific economic impacts of biodiversity loss are generally hard to exactly quantify, given the large uncertainty (and philosophical challenge) surrounding the assignment of economic values to for example the loss of a species or a specific ecosystem service. The challenge of comprehensively evaluating economic impacts of biodiversity loss has also been reviewed by Dasgupta 2021, who states that "*Nature's worth to society – the true value of the various goods and services it provides – is not reflected in market prices because much of it is open to all at no monetary charge*", or that externalities of economic development and thus true environmental costs are rarely included in impact assessments (Dasgupta, 2021). Common economic measures such as GDP do not account for the depreciation of common assets, including the natural environment. Given that the amount of available natural capital per person has declined by about 40% between 1992 and 2014 (Dasgupta, 2021) and that feedback between biodiversity and economic sectors - for example the specific economic loss of a pollinator species on food production - are poorly if at all quantified, uncertainties of likely economic impact of biodiversity loss are thus expected to be huge. Nevertheless, there are some assessments that have attempted to approximate the value of biodiversity, or efforts to conserve it, in monetary terms (Balmford et al., 2002; Dasgupta, 2021; Waldron et al., 2020), although the uncertainties in either are likely to be large.

Economic impacts of biodiversity changes are commonly estimated either by assuming that there is an existing market or demand for certain ecosystem services of Nature Contributions to People (Costanza et al., 1997), or by translating the implications of managing biodiversity into economic costs. As a recent example for the former, a World Bank financed report broadly assessed the economic effect of changes in Nature Contributions to People using the InVest model (Johnson et al., 2021). They found that within the EU, the output of sectors that directly or indirectly rely on such contributions (e.g. agriculture, livestock, forestry production, and fisheries sectors) could decrease by 5% ($28 billion) by 2030 (Johnson et al., 2021). OECD (2015) used a Willingness-to-pay (WTP) approach to estimate the damages of the loss of Nature contributions to the economy. For all the three groups of OECD countries in Europe (EU large 4, Other OECD EU, Other OECD) analysed, 0.5% of GDP in 2060 is estimated as WTP for RCP6.0, and 1.1% of GDP for RCP8.5.

Similarly, another report estimated the economic implications of expanding protected areas up to an amount of 30% of terrestrial land, a key target in European and global biodiversity policies. Compared to in-action, Waldron et al. found that expanding protected areas would also generate economic profits, estimated to be in the range of an extra $64 billion - $454 billion per year by 2050 (Waldron et al., 2020). The underlying assumption here is similar as above, specifically that protected areas provide a range of services in terms of tourism and spillover effects of ecosystem services. Previous reports by the European Commission estimate the value of the European protected area network to be in the order of €200 to 300 billion/year (European Commission. Directorate General for the Environment., 2013). At the same time, the enforcement of conservation measures also can imply restrictions and leakage effects on existing land use (Staccione et al., 2023). Recent approaches have taken land-use constraints from IAM as input to guide the placement of conservation efforts to avoid leakage effects (Chapman et al., 2023), but so far this work has often ignored economic costs as a factor particular in Europe owing to a lack of good spatial data (Armsworth, 2014).

Finally, the most straight-forward approach towards linking economic impacts to biodiversity changes, is to estimate the current and added economic costs of conserving biodiversity (White, 2022; White et al., 2022). Here the assumption is that protected areas and nature conservation measures provide both biodiversity and society benefits, but are costly to sufficiently maintain and such costs need to be taken into consideration if we are to achieve biodiversity conservation targets. Costs for managing biodiversity for example include land acquisition, staff costs or payments of subsidies. Such conservation management costs can be estimated under a range of climate and development scenarios (Wintle et al., 2011). However they can also include costs of threat abatements, for example such as the rising costs of managing impacts of invasive alien species (IAS) in natural ecosystems and protected areas, whose spread is often facilitated by climate change. Here existing costs of IAS in Europe have been estimated up to US$140.20 billion (or €116.61 billion) between 1960 and 2020 (Haubrock et al., 2021; Henry et al., 2023), the majority (>60%) of which are costs related to economic damages rather than mitigation. Clearly there is a need to consider the economic impacts of conserving and managing biodiversity more widely.

Adaptation: costs and effectiveness

Many climate adaptation measures are closely intertwined with ambitions to conserve biodiversity, primarily through the role of Nature Based Solutions (NBS) which are expected to play a large role both for climate adaptation and mitigation (Seddon, 2022). NBS enable the alignment of different policy agendas and overwhelmingly (88%) provide benefits for both climate adaptation and biodiversity (Key et al., 2022). For example, actions such as the restoration of forests, riverine or coastal vegetation can bring large benefits by preventing floods, improving human health and other services such as pollination or clean water (Borras & Franco, 2018; Burch et al., 2014; Key et al., 2022). Targeting biodiversity specifically, climate adaptation measures usually aim at increasing resilience or target the conservation of climate refugia and future expansion areas (Carroll et al., 2010; Stralberg et al., 2020).

Since nature contributions to people are usually higher in areas that are managed for conservation such as protected areas, it is key to identify synergistic areas that bring the largest climate change adaptation benefits to society, while also maximising biodiversity benefits and enable functioning ecosystems to thrive (Key et al., 2022; Villarreal‑Rosas et al., 2023). Waldron et al. (2021) through a partial assessment found that

expanding forest conservation efforts had an avoided-loss value of \$170-\$534 billion per year by 2050, largely reflecting the benefit of avoiding the flooding, climate change, soil loss and coastal storm-surge damage that occur when natural vegetation is removed (Waldron et al., 2020). Similarly, the strategic spatial allocation of NBS could provide benefits up to half the (opportunity) costs compared to establishing them in a non-optimized way (Strassburg et al., 2019; Villarreal‐Rosas et al., 2023), highlighting the potential for the spatial allocation of biodiversity-conscious and economically cost efficient NBS interventions at the European scale. This can also ensure to minimise displaced land use and maladaptation practices for biodiversity.
In Europe the economic costs of managing biodiversity in the context of climate adaptation, have traditionally been ignored, although methods have been proposed to link conservation management (such as for protected areas) with economic costs (Wintle et al., 2011). The reason is likely the lack of spatially-resolved costing estimates. For example less than 10% of studies and case-study reports do provide estimates of biodiversity related management costs (White, 2022). Future studies should try to identify options for managing and integrating biodiversity perspectives and climate adaptation jointly to maximise synergies across policy objectives (Arneth et al., 2023; Villarreal‐Rosas et al., 2023), while doing so in an economically cost-efficient manner to facilitate implementation.

Key gaps

In general, although climate impacts on biodiversity are well quantified, the **economic implications** of biodiversity change remain poorly understood and quantified from almost every point of view, especially given the importance of biodiversity for European agriculture, tourism and human well being.

Little to no data is openly available on the costs and impacts of European nature **conservation efforts**.

Benefits of climate adaptation are not aligned with biodiversity conservation objectives.

Biodiversity related economic estimates are usually on the supply side and linked to the provision of Nature Contributions to People (NCP) or Nature-based solutions (NBS).

Most promising approaches are those that identify economically cost-efficient climate adaptation options that also co-benefit biodiversity.

A possible first level of analysis could account for the economic costs and benefits of managing species of conservation concern under different climate scenarios.

Some modelling improvements need to be implemented:

- Current biodiversity impact models tend to focus on the broad-scale implications of climate change, and less on sub-annual climatic extremes (fires, droughts, etc). Existing impact models (Jung, 2023) would need to be updated and customised to cover such risk factors.

- How and where biodiversity should be managed under different European climate pathways (mitigation or adaptation) is not clear. Existing spatial optimization methods (Chapman et al., 2023) could be customised to account for different NBS that would bring adaptation benefits.

- Biophysical potentials for NBS from other ACCREU tasks (e.g. spatial-explicit coastal adaptation options) can be integrated into such climate-conscious conservation planning exercises (Villarreal‐Rosas et al., 2023)

- Economic benefits of managing and conserving biodiversity could be estimated through meta-analyses or econometric analyses, estimating for example the future aggregated costs of managing protected areas (staff, invasive species, climate adaptation portfolios, ecosystem restoration).

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8. Social justice and distributional implications

Exposure to climate hazards varies considerably between and within European regions, across geography, but also with socio-economic factors and demographic characteristics (EEA, 2022; EC, 2022). The combination of high exposure and vulnerability has also been named **'climate disadvantage'** (Lindley et al. 2011). Climate disadvantage can be further exacerbated by **unequal capacities to adapt**. Adaptive inequality can be due to **structural conditions** (e.g. living in areas where agriculture is the primary employer with few alternatives to non-manual labour); or due to **individual circumstances** (e.g. ability to pay for air conditioning as a way of combating heat stress, leading to a so called 'cooling gap' between those who can afford the technology and those who cannot, Andrijevic et al. 2021; EEA, 2018). For example, unequal health outcomes can be further affected by determinants of vulnerability including age, gender, mobility, ethnicity, preexisting health conditions, household income, housing quality or extent of social networks (EEA, 2022; WHO Regional Office for Europe, 2021).

Large-scale modelling analyses of climate risks have not examined social justice implications and considerations of social justice are only beginning to be integrated in the national adaptation plans (Nightingale et al. 2020; Holland 2017; Eriksen, Nightingale, and Eakin 2015, Lager et al. 2023). **Social and**

environmental justice frameworks can help understand which populations and groups are affected by climate impacts and adaptation interventions. A social justice lens also supports the identification of gaps in existing structural conditions and policies and how to identify strategies to reduce unequal exposure and vulnerability. There are many different ways of understanding social justice, but at its core, it is concerned with the **principles of participation/procedure, distribution, capabilities, consideration of rights and responsibilities as well as recognition and restorative action to address historical harms** (Holland 2008; Schlosberg 2012; Bulkeley, Edwards, and Fuller 2014; Juhola et al. 2022). In the context of evaluating the distributive aspects of public policies, welfare and well-being can be considered as an additional metric to determine the social justice of adaptation interventions (Persad 2019). Some research has focused specifically on the different ways in which justice and health intersect (Wiley 2014; Asada and Schokkaert 2019). Wiley (2014) for example, has proposed a specific **'health justice'** lens which emphasises the need for a broader inquiry into social determinants of health, addressing social and cultural bias in healthcare measures, and promoting collective action through community engagement. Another concept that is considered in the EU adaptation strategy is that of just resilience, which includes two components, 1) the distribution of benefits and burdens of adaptation responses among social groups and 2) the unequal distribution of climate impacts and risk due to unequal exposure, pre-existing inequalities and differences in adaptive capacities and capabilities (Lager et al. 2023).

Analysis of social justice in climate adaptation policy

Methodologies to assess the social justice dimensions of adaptation policy are only recently beginning to emerge. The United Nations Economic and Social Commission for Western Asia (ESCWA) 2021 **Social Justice Policy Gap Assessment Tool** provides a structured methodology for analysing social justice, quantifying compliance with social justice principles, identifying policy gaps, and suggesting interventions. It strives to integrate social justice into policies, enhance transparency, inclusiveness, and participation in policy development and implementation. While it includes a standard question list, it can be tailored to specific national needs. Juhola et al. (2022) present an **Adaptation Justice Index (AJI)** designed to evaluate and compare the justice dimensions of climate adaptation strategies. The index provides a comprehensive view of the justice aspects of adaptation plans and strategies, allowing for analysis and comparison across different societal contexts and levels of governance. The AJI can be used to evaluate the fairness of the adaptation planning process, including who can participate, how decisions are made, and whose information or ideas are considered. This index was tested using an extreme case sampling method, selecting cases from both Europe and North America to demonstrate the sensitivity of the index in capturing differences between cases in similar contexts. The results showed that the procedural and distributive dimensions of justice received relatively high scores, indicating fairness in the process of climate adaptation planning and the equitable distribution of climate impacts and resources. However, the recognitional and restorative dimensions received lower scores, suggesting the need for improvement in recognising historical disadvantages and addressing past injustices. Heyen (2023) proposes **three categories for analysing climate justice** within adaptation planning: adherence to justice principles; level of social inequality; and social impacts of climate and environmental policies. These categorisations allow for the systematic identification of a broad range of inequalities and their evaluation according to different justice principles. This framework aims to facilitate the detection of intersectionality, policy trade-offs, and normative judgments in research and policy assessments. Through the application of such frameworks, ex-post assessments can be made to account for potential inequalities in adaptation policy. Additionally, targeted measures can be developed ex-ante to ensure that these inequalities are accounted for within heat adaptation planning.

Quantitative assessment of distributional effects

In terms of quantitative analysis, until now the literature has offered few quantifications of the heterogeneous vulnerability of EU citizens, but mainly focuses on the distributional implications of mitigation policies (Fragkos et al, 2021, Vandyck et al. 2021). The topic of distributional implications of climate change impacts and adaptation actions is even less analysed. Campagnolo et al. (2023) provide a first comprehensive assessment of the economic costs of climate change impacts and adaptation for EU27 households across three different socioeconomic groups and project the implications around 2050. The study statistically assesses the **empirical** relations between **climate-related hazards** (mean temperature, Cooling Degree Days -CDDs-, Heating Degree Days -HDDs-, Standard Precipitation Index -SPI-, and burnt area), various expenditure types from Eurostat HBS (health, food, energy, insurance, total expenditure), and income sources (sectoral labour income, total labour income, imputed rent, and monetary income). Climate-induced **health expenditure** of EU households marks the highest increase among all expenditure types (0.3% and 6.2% under SSP2-4.5 and SSP5-8.5, respectively) in a regressive manner (higher increase of expenditure for poor than for rich households) in the Southern EU. Climate change will also cause an increase in average household **food expenditure** in most EU countries, between 0.81% and 0.74% under moderate and severe climate change scenarios, with regressive implications in the Eastern EU. **Energy expenditure** will slightly drop in the EU, between 0.5% and 1% across climate change scenarios, due to a contraction of gas expenditure by 14% (19%) observed across all EU under the SSP2-4.5 (SSP5-8.5) scenario. This result masks a moderate increase in electricity expenditures by 3.3% (4.2%) under the moderate (severe) climate change scenario. Poor households would need to increase electricity expenditure relatively more than rich ones in the Northern and Southern EU.

Climate change will also influence income sources. Overall impacts on **labour income** are small (0.73% and -0.02% under the moderate and severe climate impacts). At the EU level, moderate (severe) impacts increase agricultural income by 5.5% (8.6%), industrial income by 2.4% (0.8%), and service income by 4.3% (1.7%). The magnitude of impacts is very different across sectors and ranges between -50% and 150% in agriculture, and -20% and 10% in industry and services. The income loss in the Southern EU affects poor households more than rich ones and impacts, while lower in magnitude are similarly regressive in the Northern EU under severe climate change.

The overall climate change impact on **income sources** (monetary net income including labour income, asset value and social transfers, net of taxes) is negative in the EU, meaning that they fall by 0.8 % (1.1%) under the moderate (severe) climate change scenario. Monetary net income shrinks across almost all income groups and macro-regions, probably due to the negative effect on investments and rent revenues, despite the redistributive effect of social transfers. The highest losses are observed in the Southern EU. The impact is progressive in all macro-regions excluding the Northern EU region under severe warming.

To summarise, the study highlights that there are some regions in the EU experiencing a reduction of income and a simultaneous increase in expenditure, both affecting disproportionately more the poorest household class. In the Southern EU, there is an increase in health, electricity and insurance expenditure and a reduction in total labour income. For the Northern EU, increases occur to electricity expenditure, insurance expenditure, labour and monetary income, and in the Eastern EU increases apply to food expenditure.

Randazzo at al. (2020), using an **empirical model**, examines the distributional implications of electricity demand for cooling in some EU countries (France, Spain, Sweden) and shows that climate change and the growing demand for air conditioning are likely to exacerbate energy poverty. In Europe, the population affected by fuel poverty ranges from 9.7% to 15.11%, depending on the member state (Atanasiu et al., 2014) and the number of households spending more than 5% of their income on electricity will slightly increase in these countries.

Using a **modelling approach**, Bachner et al. (2023) finds differentiated implications of climate change across income quartiles and time in Austria, with the short-run impacts of flood events strongly affecting the richer quartiles where capital is concentrated. Over time, the richer quartiles recover more quickly.

Key gaps

- There is firstly a need to go beyond the status-quo of simply identifying which groups are at risk. Healthcare professionals, for example, require **training** to offer targeted support to at-risk subgroups and to engage both health service users and providers in adaptation planning and implementation to integrate differential and dynamic vulnerabilities as well as social justice concerns (EEA, 2022; WHO Regional Office for Europe, 2021).

- Understanding these **nuances around risk and vulnerability** and ensuring **participation and engagement** is the first step to ensuring that adaptation policy can work to reduce health disparities and promote fairness in the distribution of adaptation benefits (Juhola et al. 2022).

- There are currently considerable gaps in the evidence base about the **effectiveness of initiatives** to address changing vulnerabilities and respond to the differential effects of adaptation and need to be complemented with processes of monitoring and evaluation (EEA, 2022; WHO Regional Office for Europe, 2021).

- There is a need for **more empirical evidence on the impacts of adaptation policies on marginalised groups**, a deeper exploration of the intersectionality of climate justice issues, and the development of practical tools for assessing and implementing social justice principles within policy frameworks.

- Most of the **climate impact assessment literature** has focused on the direct costs or the economy-wide costs, and have analysed the output for aggregate indicators such as GDP or sectoral output. **The impact on households is in general disregarded and so is the distribution across household types.** The few papers going in this direction have however a limited representation of household heterogeneity, i.e. it mainly relies on the income class the household belongs to, disregarding other socioeconomic factors, such as age and disability, that alter the vulnerability to climate change impacts.

- The **empirical literature** is still narrow and usually sector-, commodity-, and region/country specific.

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9. Financial and fiscal implications

Economic impacts of climate change on financial and fiscal systems

Climate change has important effects not only on the real economy, but also on financial markets. Emerging evidence indicates that this transmission channel could be potentially very important as **a source of systemic risk** and could have consequences for the real economy as well. For instance, Mandel et al. (2021) investigate the transmission of coastal and riverine flood risks by 2080 and find that European countries of key relevance in the financial system, such as the UK and the Netherlands, could act as amplifiers of risk and they find global consequences being a manifold of the direct impact of flooding within the country.

While there is a vast body of literature on the role of the insurance sector, literature on the role of **financial markets as transmitters of physical climate risks** is still comparatively limited, at least in terms of modelling (Campiglio et al., 2023; Battiston et al. 2021; Lamperti et al. 2019). More attention has been paid to the interactions between financial risk, climate change transition risk, and asset stranding induced by the transition away from fossil energy sources (Battistion et al 2021), while only a few studies analyse how physical climate change risk can impact firms' operations and profitability, with subsequent negative effects on the risk return profile of investors' portfolios and investment prospects (Klusak, et al. 2021). Central banks, including the European Central Bank, have started to conduct climate stress tests not only for transition (mitigation policy) risks, but also for physical risks (DeMenno 2023), and financial disclosure has been increasingly used to reveal physical risks of companies and banks.

Another trigger of potentially important consequences for macroeconomic and public finance stability that is receiving increasing attention relates to the link between climate change physical risk and sovereign risk (Volz et al., 2020). Combining climate projections with economic data and machine learning, Klusak et al. (2021) simulate the effect of climate change on sovereign creditworthiness. Results highlight detectable impacts of climate change as early as 2030, with significantly deeper downgrades across more sovereigns as climate warms and temperature volatility rises. In the EU, France and Germany are projected to experience an additional cost of sovereign borrowing larger than $5 billion in RCP8.5 in 2100. A highly indebted country like Italy could face a $ 810 million increase in the cost of borrowing.

Climate change impacts can interact with the fiscal system by inducing higher public expenditure and by reducing tax revenues (Bachner and Bednar-Friedl 2019). On the expenditure side, extreme events lead to costs of reconstructing public infrastructure, but also disaster relief payments in case of flooding or agricultural droughts (with the scale depending inter alia on whether building insurance against flooding is mandatory or not). On the revenue side, the impacts of climate change alter the tax base (value added/output, labour/income; capital and land). With higher expenditures and lower revenues, governments either need to cut expenditures or increase tax rates, with different welfare effects (Bachner and Bednar-Friedl 2019). An alternative option, which may not be consistent with fiscal stability, is government borrowing from the private sector or governments abroad as this increases the debt stock and thereby future debt service payments (Parrado et al. 2020).

Similar to climate change impacts, adaptation affects government budgets directly and indirectly. A few studies assess the net benefit of adaptation from an economy-wide welfare perspective and find that adaptation can improve welfare when considering both benefits (avoided benefits) and costs (investment costs; maintenance costs). For coastal protection against sea-level rise, Parrado et al. (2022) find that coastal adaptation is highly effective in reducing damages and that the fiscal deficit is lower in 2050 than without adaptation (and with climate impacts), despite substantial upfront investment costs into dikes. Bachner et al. (2019) assess public adaptation expenditures in Austria across 10 impact fields and investigate how different fiscal counterbalancing approaches (reducing transfers to households, increasing capital tax or labour tax or valued added tax) affect economic indicators. Except for increasing labour taxes, all counterbalancing approaches lead to positive (yet small) effects on GDP, welfare and employment. A related strand of literature looks into the question of the sustainability of the European Solidarity Fund (EUSF; now part of the Solidarity and Emergency Aid Reserve) as a risk pooling mechanism, among EU member states and finds that not only the increasing frequency of events but also the compounding nature of river flooding in Europe can lead to a more frequent depletion of the EUSF (Hochrainer-Stigler et al. 2023). This risk of depletion is furthermore increased when considering events in European outermost regions (Cuillo et al. 2021).

The role of insurance as adaptation measure

When accounting for economic impacts of climate change, adaptation possibilities can be either the **prevention and limitation** of the impact itself, through implementation of defence strategies against extreme events (i.e., dike upgrade and beach nourishment), but also through **transferring the climate risk to counterparties** that are better equipped to bear it. Risk insurance can provide a financial safety net against the negative impacts of extreme weather events at the individual, community, regional, and national levels, typically for events of low frequency/medium severity. **Risk transfer strategies** involve pre-disaster financing arrangements that shift economic risk from one party to another (IPCC, 2012). In particular, climate risk insurance can provide a financial safety net against the negative impacts of extreme weather events at the individual, community, regional, and national levels, typically for events of low frequency/medium severity.

However, the spatio-temporal correlation of climate risks pose challenges for transferring risk at the aggregate level. This results in assets not being insured (because of the high insurance premium) or even being uninsurable. The risk of uninsurable assets has been described by Bubeck et al. (2019) who particulary focused on the inability to insure losses to public infrastructure (with typical very high indirect costs).

Climate insurance can take different forms depending on the target clientele and payment mechanisms. Policyholders and insured values can be identified at the micro, medium, and macro levels, from low-income households, characterised by small premiums and small amounts insured, to sovereign insurance, underwritten by regions or countries. The payment mechanism can be based on actual losses (traditional approach), or on index or parametric solutions (based on a trigger that leads to the provision of a predefined payment) (Hermann et al., 2016). Climate insurance helps increase resilience through several mechanisms. The simplest is to finance recovery by providing financial support to those affected. Risk reduction measures can be included in insurance products such as incentivizing risk reduction measures in property insurance, promoting proactive business interruption risk management, or improving creditworthiness through adaptation measures (Scholer, M., Schuermans, P. 2022).

Flood insurance

Studies on **flood adaptation costs** address either sea-level-rise related flood costs or the river-related ones. Studies on sea-level-rise costs generally evaluate adaptation costs in terms of dike upgrade and beach nourishment. Flood protection measures reduce the probability of certain areas being flooded by a 100-year flood, but at the same time they create an illusion **of safety** and “encourage” communities to overdevelop the protected flood-prone areas. The overall risk, determined by the product of the (reduced) probability of flooding may therefore increase.

People in recurrent affected areas seek insurance, while those who live some distance from a river are not interested in buying cover. Because of this, flood insurance still has low average penetration in Europe. For private homes and small businesses and their contents the annual premium can be lower than many people think: in Germany premium starts at an affordable level of roughly €50 (in May 2019) in low-risk areas.

Transferring to insurance the residual risk is highly recommended for areas with recurrent river flooding, while it is not known with sufficient lead time where and when a flash flood resulting from intense rainfall will hit. At the same time, the probability of being hit is so small that expensive structural flood protection measures are not reasonable compared to loss expectation.

While there is limited information on household level **risk perception** and mitigation efforts at the European scale, **understanding social and behavioural drivers** and constraints of household adaptation is essential to effectively address increasing climate-induced risks. Factors shaping household adaptation are commonly treated as universal, while emerging understanding shows that adaptations are shaped by social, institutional and cultural contexts, despite countries' differences. Using original surveys in the United States, China, Indonesia and the Netherlands, Noll et al. 2022 explore variations in factors shaping households' adaptations to flooding. Factors such as trust in governmental protection, or addressing damage responsibility to the government, have negative effects on households' adaptation intentions, as well as an ageing population is less likely to adapt. On the contrary, perceived probability of damage and prior flood experience, as well as influence of traditional media, has little or slightly negative effect on motivating household adaptation. Surprisingly, beliefs in ongoing climate change seem to have negative effects on adaptation intentions, perhaps because households with a sense of urgency have already adapted. Climate adaptation policies need to take into account that socio-behavioural drivers may discourage household adaptation motivation.

Incentivizing **autonomous risk mitigation** can be supported by creating a risk "price signal" that encourages households to avoid risk or take risk-reducing measures (Tesselaar et al. 2020). In purely market-based insurance systems, premiums are set according to risk. The riskier one's prospects, the costlier one's insurance. This type of insurance is found to substantially limit the increase in risk due to climate- and socio-economic change (Tesselaar et al., 2023). Moreover, since the insurers in these systems are private parties, the premiums will cover expected costs in excess. A rational insurer, out to make a profit, will not accept insurance that is expected to bring about a loss. These characteristics can make commercial **insurance markets unappealing when it comes to climate change** (Will M. et al. 2022). As a result of climate change, the increase in flood risk may cause substantially higher risk-based insurance premiums. Because of this, the uptake of flood insurance in voluntary markets may decline when flood risk increases, as a result of climate change (Tesselaar et al. 2020). While disaster insurance coverage can enhance financial resilience of households to changing flood and other risks caused by climate change, income inequalities imply that not all households can afford flood insurance, and residual damage arises. The actual extent of residual impacts though also depends on the extent of adaptation implemented at the regional or community level.

Hudson et al. 2019 evaluate the ability of flood insurance arrangements in Europe to cope with trends in flood risk. Results show that the average risk-based flood **insurance premium could double** between 2015 and 2055 in the absence of more risk reduction by households exposed to flooding and if no flood insurance market reforms are undertaken. There is limited information on household level risk perception and mitigation efforts at the European scale. Average household insurance premium that is lowest in the solidarity public structure (€5–€125 per year in 2015) and highest in the private voluntary markets (€30–€2000 per year in 2015). These differences in premiums translate into different rates of unaffordability due to the differing degrees of cross subsidisation between high- and low-risk households. For instance, the voluntary private insurance premiums are unaffordable for about 21% of the regional population in high-risk areas (on average), whilst this is only 16% in the public private partnership (PPP) market. Households with insurance coverage will be exposed to a potential premium discount if the household employs damage mitigation measures. This may promote a household to employ a mitigation measure if it did not do so initially. The more strongly premiums are risk based, the stronger this incentive will be (e.g., in the solidarity public structure, incentives are negligible). Part of the expected future increase in flood risk could be limited by flood insurance mechanisms that better incentivize risk reduction by policyholders, which lowers vulnerability.

The affordability of flood insurance can be improved by introducing the key features of public-private partnerships (PPPs), which include public reinsurance, limited premium cross-subsidization between low- and high-risk households, and incentives for policyholder-level risk reduction. By using an adaptation of the "Dynamic Integrated Flood and Insurance" (DIFI) model, Tesselaar et al. 2020 analyse whether the functioning of a formal flood insurance system is hampered by diminishing demand for coverage, and when such a tipping-point can occur in Europe for current flood insurance systems under different trends in future flood risk caused by climate and socio-economic change. Results show **rising unaffordability and declining demand for flood insurance** across scenarios towards 2080. Under a high climate change scenario, simulations show the occurrence of a socio-economic tipping-point in several regions, where insurance uptake almost disappears. As a result, regional inequalities arise in the ability to use flood insurance as an instrument for adapting to increasing flood risk. A progressively rising flood insurance premiums is observed over time from the climate change scenario of +2,81°C to +4,31°C, for countries that maintain risk-based insurance premiums. This causes an increase of unaffordability of insurance, the extent of which depends on the projected socio-economic development in that period. Such unaffordability problems occur particularly in regions with below average income per capita. This process causes flood insurance demand to almost disappear for several European regions. The **collapse of private flood insurance** calls for a shift of flood damage compensation from pre-funded, formal insurance, towards less formal means of financing, such as ex post government compensation or self-insurance.

Surminski et al. 2015 reflect on how to use insurance as a lever for risk reduction and prevention efforts and whether and how current EU policies influence flood insurance and how this interplays with the national policy level. The wide variety of existing insurance schemes, as well as different supply and demand patterns, shows that there is no 'one-size-fits-all' solution, and so there is wide agreement that a complete harmonisation of flood insurance offering across the EU is unlikely to be effective. While the current schemes are influenced by public policy, directly or not, the paper shows ample evidence that insurance, or risk transfer in general, can boost resilience to natural hazards more effectively than ex-post disaster aid, but significant challenge for financial compensation mechanisms are expected, unless more risk reducing measures are applied, such as flood defences, stricter building codes and/or land-use (zoning) policies.

Because climate change will cause a rise in risk‑based premiums, the possible **collapse of insurance markets** for extreme weather risks was projected by Botzen et al., 2020 (COACCH D3.4). The consequent decline in insurance uptake can substantially affect the viability of flood insurance markets, and they can collapse in a range of regions across Europe. This process exacerbates the vulnerability especially in regions where insurance is voluntary, and households face unaffordable premiums due to either low income or high risk. A socio‑economic tipping point can occur when uptake of flood insurance diminishes as a result of rising premiums due to climate change, low income, or low willingness‑to‑pay for insurance. Regions where such a tipping point is projected in the future include Croatia, Bulgaria, Czech Republic, Poland and Portugal. As **flood insurance markets may cease to exist** in these regions, while the risk of flooding is expected to increase, households will become more financially vulnerable to flood damage. Also, from a macroeconomic perspective, the tipping regions in the Czech Republic and Poland are among the most affected. Additionally, severe impacts can be observed for the Netherlands, Germany, Austria and Italy.

Furthermore, alongside the ongoing research focused on flood insurance for households, there is an increasing interest in studying the effects of business interruptions. Employing the Random Forest methodology, recent findings, such as those by Sultana et al. (2018), highlight that the presence of insurance in this scenario serves as a catalyst for implementing adaptive measures at the company level. Lower insurance coverage may require governments to provide compensation for uninsured parties experiencing flood damage. In fact, it may be politically unfeasible for governments to refrain from providing financial aid to uninsured victims in the aftermath of a flood, particularly in EU welfare states. This implicit liability for governments to provide aid is found to reduce the incentive to obtain insurance coverage (Kousky et al., 2018; Andor et al., 2020), and increase the future extent of this liability (Tesselaar et al., 2022). A lower coverage of flood risk by insurance is also found to complicate public finances, both through increased spending on reconstruction and lower tax income through reduced economic activity (Knittel et al., 2023). Besides this, low insurance penetration rates cause negative impacts on savings and, therefore, investments, which in turn reduces capital accumulation. Finally, negative impacts on GDP are significant across EU regions, and even larger on welfare when accounting for additional consumption for reconstruction not being welfare enhancing (Knittel et al., 2023).

Key gaps

Further research is needed to delve into the role of insurance for businesses in mitigating flood risks, particularly considering that existing studies in this domain predominantly concentrate on agricultural businesses and forest (fires)(e.g., Barreal et al., 2014; Brunette et al., 2017).

For the fiscal implications of adaptation, further research is needed on:

- The welfare benefits of different types of adaptation beyond infrastructure investment, such as early-warning systems, heat action plans, nature-based solutions etc.

- Soft and hard limits of adaptation options for different RCP-SSP combinations, replacing the default assumption of uniform damage reduction potentials

- Different adaptation intensities (keeping expenditures constant or expanding it; keeping protection levels constant), e.g. also reflective of different SSP narratives

- The sustainability of risk sharing mechanisms across European countries (Solidarity Fund), considering compound risks and feedbacks to government budgets

- Stress testing of government budgets, considering that governments are providing assistance of last resort to households and companies

- Assessment of fiscal implications at lower governance levels (provincies/states; municipalities)

BOX 9. Models and Methods

Several analytical model types can be used to study the financial, fiscal and insurance implications of flooding and other climate change impacts. Macro-economic assessment applying Input-Output models and Computable General Equilibrium models are most widely used in this context (Koks et al., 2016). Those models allow analysis of both the direct (i.e. damage) and indirect impact of floods as they both build upon social accounting matrices which quantify all monetary flows between all sectors in an economy (Botzen et al., 2019). The fiscal implications of climate change can be studied with computable general equilibrium (CGE) models. In these models, climate change impacts are included via different channels: by reducing factor productivity (e.g. labour productivity because of heat stress), by increasing costs of sectoral production (e.g. higher costs for irrigation water), by changing endowments (e.g. destruction of land due to coastal flooding) or by changing demand (e.g. higher cooling demand increases demand for energy; costs of rebuilding of destroyed buildings after flooding or storm events). Usually, these sectoral damage costs (expressed in expected annual damage, usually averaged over climate periods of 20 to 30 years) are derived from biophysical and sectoral models that are driven by different RCP-SSP scenario combinations. The CGE model then computes the indirect effects on the economy, by considering sectoral interlinkages (e.g. from the agricultural sector to food and hospitality sector) and prices work as a market clearing mechanism. But in addition to effects on different economic sectors and households, the public sector is affected directly by climate change impacts in the form of destroyed infrastructure (capital endowment) and e.g. disaster relief payments to households after a flood event. In addition, public finances are affected indirectly by changing the tax base (lower household income, lower GDP and value added). Different financial closure rules are used to ensure that public expenditures (government consumption; transfers to households; interest payments) balance with public revenues (tax revenues). One option is to increase public debt (deficit spending), but this may not be consistent with fiscal stability. As alternatives, tax rates or transfers can be required to adjust endogenously in the CGE model to keep the debt-to-GDP ratio constant. The outcomes of the CGE model allow a comparison of these different closure rules not only in terms of GDP and welfare, but also in terms of social groups and different sectors.

CGE models like COIN-INT and ICES-XPS are also capable of modelling adaptation by including the cost of adaptation for specific sectors, private and public households. A detailed understanding of the type of adaptation (grey, green, soft), the structure of costs (investment, operating/maintenance, opportunity cost of labour) and who is actually bearing the costs (public vs private sector) is needed to meaningfully assess the costs and benefits of adaptation in such models. This information is usually derived bottom-up from national adaptation strategies and plans and complemented with information on adaptation effectiveness from biophysical and sectoral models as well case studies (e.g. from the ECONADAPT repository). For the public household, adaptation usually comes with an upfront investment that pays off in later periods, leading to a net benefit on the macroeconomic scale. It is therefore useful to assess the effect of adaptation not in a static but in a recursive-dynamic CGE model. Expanding on the macroeconomic perspective, Integrated Assessment Models (IAM) offer a holistic evaluation of climate and economic factors to project the forthcoming economic consequences of climate change. Advanced models like the CLIMRISK-RIVER model (Ignjacevic et al., 2020) concentrate on predicting flood-related future impacts, emphasising the importance of incorporating precipitation data into assessment frameworks. These models enable the explicit modelling of flood adaptation measures, providing valuable insights into effective strategies for managing and mitigating flood risks.

Partial equilibrium models, unlike CGE models, concentrate on the effects within a specific sector. Particularly valuable in exploring the insurance-related impacts, models such as the Dynamic Integrated Flood Insurance (DIFI) model, utilise climate and socio-economic data to forecast yearly flood damages and variability for households in high-risk zones until 2050. The DIFI model quantifies insurance premiums and subjective flood risk, offering insights into future risk and coverage (Tesselaar et al., 2022). Worth mentioning in this context are also agent based models such as those applied by de Ruig et al. (2023). Those models can account for complex interactions and dynamic behaviour of consumers and insurers in the climate insurance market. Partial equilibrium models such as the CATastrophe SIMulation (CATSIM) model are also used to assess fiscal stress from flooding or tropical storms (Hochrainer-Stigler et al. 2017). These models use probabilistic information e.g. on the hazard of riverine flooding and combine this information with projections on exposure and vulnerability to derive monetary losses from such events. If the monetary loss exceeds a predefined threshold (e.g. x% of GDP as a measure of fiscal space) a country becomes fiscally stressed.

Finally, empirical studies utilising econometric methods enable a comprehensive analysis of both the direct and indirect effects of floods. These studies often draw data from the Emergency Events Database (EM-DAT), curated by the Centre for Research on the Epidemiology of Disasters. Additionally, databases like NatCatSERVICE and Sigma, developed by reinsurance giants Munich Re and Swiss Re, offer comparable information, although their widespread availability to the public is limited (Botzen et al., 2019).

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10. Socio-economic tipping points

In addition to the climate-induced sectoral and macro-economic impacts, there is a set of **additional potential abrupt non-linear impacts** from climate change often termed tipping points. Climate tipping points relate to critical thresholds at which a small change can alter the state of a system fundamentally. A number of global (earth-system) climate 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 and they can be potentially abrupt, non-linear and irreversible. These 'bio-physical' climate tipping points provide a further justification for global mitigation policy, yet they are poorly represented in economic assessments of climate change. To propose a common definition and some guiding criteria to define what a tipping point is not so easy and there is not always consensus about a definition among scholars (Van Ginkel et al., 2020). Following the definition adopted in COACCH project, to be considered a proper tipping point a certain phenomenon needs to fit in these characteristics: (C1) Small causes with (disproportional) large effects (non-linear causal relationship); (C2) rapid, quickly occurring change; (C3) Structural reconfiguration or transformation of the affected system (Van Ginkel et al., 2020). Some additional criteria can be (C4) the irreversibility (at human time scale and with available resources) of the process, and (C5) the function of feedbacks as system-internal drivers for further feedback as well as state stabilisers.

Beyond the general definition of the determining criteria for a tipping point, there are four focus areas that can be found in the literature on tipping points. The first three define critical thresholds at which a system abruptly shifts from one state to another due to a small change in conditions (Scheffer et al., 2009). These shifts can take place in (i) the climate; (ii) ecological or (iii) socioeconomic systems. The fourth area is policy tipping points, representing fundamental changes in actions or policies in response to climate change (Tröltzsch et al., 2018). In this chapter we will mainly refer to the ones related to the socioeconomic system, namely the Socio-economic tipping points (SETP). They can be defined as a climate change induced, abrupt change of an established socio-economic system's functioning into a new functioning of fundamentally different quality. In this, the stakeholder's perception of the critical threshold for the economic system can be relevant in defining the threshold itself.

Giving a strict definition of tipping points into the socio-economic domain is challenging, as there are various types of pathways that could unfold. One possibility involves climate change acting as the catalyst for a significant socio-economic event, akin to a major shock. Another possibility is that climate change, surpassing a certain threshold, starts affecting the workings of a well-established socio-economic system. In either case, feedback loops and amplification may come into play, making the process non-linear and irreversible. Moreover, SETPs can occur even in the absence of climate tipping points when gradual climate change has large implications for socio‑economic systems. Consequently, these events could lead to a rapid escalation in expenses, for instance, manifesting as a substantial decline in the GDP of a region, or they may necessitate a complete rebuilding of an existing system, incurring substantial associated costs. These changes may arise directly in Europe but may also involve global events that subsequently spill-over into Europe. When considering socioeconomic tipping points, the issue of scale becomes particularly crucial (van Ginkel et al., 2022a). Climate change can have significant socioeconomic consequences at a local level, where the impacts may be substantial. However, on a larger European scale, the overall impact could result to be more limited. For instance, a slight increase in temperature might be enough to force the closure of a low-lying ski resort, but it may not heavily affect the total winter sport revenues in the Alps (Tröltzsch et al., 2018, Vaghefi et al., 2021).

Beside the general definition of tipping point and its key mechanisms, the COACCH project has identified a set of SETPs, driven by different impact areas. The most important are: (i) Climate induced agriculture and food shocks, and potential land abandonment and price spikes; (ii) Migration induced tipping points, including from coastal areas due to extreme sea level rise, and from major climatic shocks; (iii) Energy and Transport tipping points, with analysis of wildfire related energy supply shocks, as well as multiple floods and transport disruption; (iv) Extreme sea-level rise, including transformational adaptation; (v) Economic tipping points, including the potential for large macro-economic impacts, (vi) Financial tipping points , including the potential collapse of insurance markets from extreme weather risks, as well as major impacts on countries and financial markets. The four studies described in the PhD Dissertation by Van Ginkel et al. (2022c) indicate that smaller-scale SETP are likely to happen earlier and with greater certainty, but there are also potential major events that could occur in Europe. A further finding is that these SETPs often have strong distributional patterns, i.e. for specific regions of Europe or particular groups. While it is difficult to assign the likelihood of these events, the modelling shows these events are associated with high-end (RCP8.5) scenarios, though also sometimes at lower warming scenarios. They can include very large impacts that would have major policy consequences at the European scale.

Results from Botzen at al., 2020 in COACCH D3.4, assess the macroeconomic implications of different SETPs, while Scoccimarro et al., 2020, analyse the point likelihood in the SSP/RCP scenario framework and the relative key climate variables likely to triggering the tipping points.

- **Migration**: the point in time, following climate anomalies and as a consequence of climatic conditions adversely affecting their livelihoods and their well‑being, when a significant proportion of the local or regional population have migrated from the area for a substantial, non-seasonal, period. The key climate variables likely to trigger or exacerbate patterns of migration include rainfall patterns, heatwaves and sea-level rise. The numbers of migrants moving from African regions to Europe is expected to significantly rise over the course of the 21st century from between 0.2 and 0.4 million annually in the first two decades to up to 1.7 million annually in the 2080s. The increase is driven by population and climate change‑ induced drought projections in Africa. Shayegh et al., 2022, project international migration flows and their implications for income inequality within and between countries in the 21st century under five shared socioeconomic pathways (SSPs). Results show that in all the SSP scenarios Europe emerges as a main destination, this leading to positive gains in economic benefits from migration, but at the cost of increasing inequality within and between low-skilled and high-skilled labour.

- **Financial tipping points:** climate change could lead to large socio-economic tipping points for the public finances of countries and in the financial markets. The analysis is based on the estimated sectoral economic costs and especially at the macro-economic level. Large‑scale climate hazards already affect credit ratings, cost of debt and of capital, but higher climate disclosure could lead to financial market anticipation of future risks in high‐risk countries, thereby leading to an occurrence of a socio‐economic tipping point before the physical impacts of climate change occur (i.e. market anticipation could bring forward the timing of localised tipping points).

- **Food and water:** a socio-economic tipping point will occur when farmer's realised production and, therefore, income, becomes so variable or low that farming is no longer viable anymore. This will lead to farmers moving out of the business, resulting in a loss of farmland and loss of rural communities. Driving forces behind this are climate-induced yield fluctuations. Due to climate change impacts on agriculture, rural abandonment is expected, with the largest cropland losses due to farmland abandonment found across all scenarios is 7% for Europe, highest in the middle and Southern parts of Europe and with specific concentrations in Southern Spain and Italy. Food prices in Europe slightly increase in most of the analysed scenarios. While GDP effects of European regions turn out to be positive in most cases, except for the more vulnerable regions ITA and MEU, where we can observe relatively strong negative effects of up to ‐0.5% lower GDP in 2050, cropland loss due to extreme events could (more than) offset positive effects from long‐run (slow onset) higher yields.

- **Coastal migration:** a tipping point for a country occurs if the average annual coastal migration relative to the country's population crosses the threshold of 0.1 and 0.05 percent annual coastal migration of total population. Large scale coastal migration within EU-countries in the 21st century only occurs under a combination of high-end SLR and failure to take appropriate protection measures. The tipping points triggered by high levels of coastal migration in societies are not expected to occur in the EU28 due to its high existing standards of coastal protection. With adaptation, migration numbers are below thresholds in nearly all cases. However, additional autonomous adaptation in the form of migration further avoids impacts.

- **Sea level rise adaptation:** a tipping point might happen in case of flood protection failure and large-scale flood disaster occurrence, i.e., a vulnerable coastal delta may possibly not recover to the original state after a disaster. In the direct aftermath of a disaster, many citizens will be displaced and under some conditions, not everybody will return after the event. For urban coastal cities, the socio‐economic tipping point could be defined as an abrupt drop in the value of real estate, as a result of sharply increased risk perception of citizens and a decreased trust in the government to successfully protect against floods in the future. Tipping points in embanked urban areas such as Rotterdam can be avoided in the 21st century even in very extreme, high‐end sea level rise scenarios provided that there is a sound, proactive flood management strategy (van Ginkel et al., 2022a).

- **Trade disruptions due to flooding** are defined as the points where flood hazards cause an abrupt and disproportionately large loss of network functionality, for example measured by loss of connectivity, travel time increase, or commuter and commercial travel time lost. Results from Van Ginkel et al. (2022b) show that tipping points in the sense of nation-wide network fragmentation are unlikely, but that they may happen on the regional (sub-national) scale. An example of this is the large-scale flood that hit the Ahr Valley in Germany, in July 2021. This destroyed many roads, nearly all railways and a large number of bridges, hampering crisis response, reconstruction work, and economic recovery of the region (Koks et al., 2022).

- **Collapse of insurance markets** for extreme weather risks: the occurrence of a potential socio-economic tipping point for flood insurance might result from disappearing demand for coverage. Climate change will cause a rise in risk‐based premiums. The thus induced decline in insurance uptake can substantially affect the viability of flood insurance markets, and they can collapse in a range of regions across Europe (Tesselaar et al., 2020).

- **Climate‐induced economic shocks:** can be defined as a point at which unprecedented shocks are experienced that could significantly destabilise the economy. Developed countries such as the EU are equally or even more at risk from climate change than less economically stable, developing countries. Results suggest that it can be expected that the EU countries could likely perceive the effects of climate change impacts as severe shocks to their economies. Severe economic shocks will possibly occur in a variety of regions in Europe during this century under high end emission scenarios. Also in low climate change scenarios many EU areas may meet the tipping point in RCP2.6 and 4.5 in a way comparable to what occurs in RCP6.0 or 8.5.

- **Electricity system failures:** failure in the electricity system (major blackouts) due to disastrous consequences such as major wildfires. Much of the land area in Europe could see extreme increase in wildfire probability by the end of the century under different RCP scenarios, this coupled with the lack of forest maintenance poses a risk both of forest fires and for the continuity of service in the event of a possible system failure, as in many cases it is a fire generated by other causes that could affect the power line (Rodriguez and Gil, 2016). Hernández-López et al., 2023, implemented a method to automate the calculation of forest fire risk areas along high-voltage power lines. The threat of major wildfires in Europe can be avoided by accelerating the investment plans for renewable energy (Scoccimarro et al., 2020).

Key gaps and limitations

- **Low coverage on adaptation costs and strategies** when it comes to tipping points has been found, in respect to "usual" (linear or not) climate induced impacts path. In general, **very few estimates are present of economic costs in case of SETPs.**

- While in COACCH D3.1 and D3.2 the definition of relevant tipping points and their characteristics are clearly exposed, in COACCH D3.4 in the exposition of results few efforts have been done in **disentangling the "average" climate change impacts and the tipping point scenario** (i.e., it is not always well defined what is the substantial difference, in terms of damages, from a more "linear" climate induced impact scenario when a tipping point occurs).

-There is in general a **lack of clear exposition of economic estimations**, both from impact perspective and macroeconomic perspective in terms of GDP, while macroeconomic implications are overall well exposed.

- While a possible climate-induced **collapse of the insurance market is an important element** for the assessment of SETPs at household dimension, this deserves more attention.

- A deeper focus is needed on **social aspects such as health, poverty, labour productivity, living conditions in cities and rural areas, (criminality?)** … In general, what have been assessed in COACCH D3.1 as tipping points to be further analysed, have found few implementations in literature, especially from the economic point of view.

- The entire field of tipping points remains a priority for climate change impacts research. Socio-economic tipping points in particular need better consideration in future research.

BOX 10. Models and Methods

Van Gingel et al., 2018 (COACCH D3.1), recognize some key-mechanisms that might lead to the occurrence of socio-economic tipping points. Clear non-linear relations between system variables (which can also be described for models) have been found. For example, a clear non-linearity is observed between temperature increase and the intensity of heavy rainfall. Research confirmed a non-linear relationship also between temperature and worked hours (Burke et al., 2015; Standardi et al., 2023). Network effects (cascading or domino-effects) can induce large effects from a small cause, with rapid changes and need of structural reconfiguration of the system. This can have particular implications in collapse of financial markets, impact of failure of critical infrastructures and impact of hazards on multi-modal transport networks. Another dealing issue is that climate change may significantly alter the costs and benefits behind alternative choices made by governments and business, leading to different decisions. This might cause a structural reconfiguration of the socio-economic system, and therefore can be considered a socioeconomic tipping point. Finally, in many cases, stock depletion mechanisms (as the systematic depletion of an aquifer) can lead to the collapse and reconfiguration of specific systems.

In order to assess how the potential impacts of relevant socio-economic tipping points can be studied using the available modelling approaches, a key step is the identification of performance thresholds, indicating the boundary between acceptable and unacceptable performance of the socio-economic system of interest. To do this, many different assessment approaches can be used, using both regression analysis, qualitative assessment and macroeconomic modelling. In this, candidate SETPs are tested based on the three necessary requirements and the two additional criteria that have been previously defined. After the threshold identification, in assessing the impact, some different modelling alternatives can be applied, depending on the type of impact accounted[13]. To give one example, the collapse of insurance markets for extreme weather risks, was found to follow all the requirements (C1 to C5) defining a tipping point and was evaluated through the DIFI and CLIMRISK models[14].

For the assessment of macroeconomic implications of selected SETPs, Botzen at al., 2020 (COACCH D3.4), use two different global, multi‑sectoral, multi‑regional, computable general equilibrium (CGE) models: COIN‑INT (developed by University of Graz) and ICES (developed by the Euro‑ Mediterranean Center on Climate Change, CMCC). While CGE models compare equilibria to each other, they do not allow for the analysis of the processes themselves that lead from one equilibrium to another. Thus, CGE models can be used to assess economy-wide effects after a system (economy) has crossed a tipping point but relies on information from other models (bottom-up models as available in COACCH) with respect to economic/sectoral parameters after the system has changed.

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11. Summary of key gaps

Key element	Quantity and quality of information	Gaps
Agriculture	In determining future yields, both climate and bio-economic models have reached a good level of spatial and temporal resolution. Most research focuses on wide economic sectors impacts or aggregated damages across countries. The study of adaptation strategies and relative cost-benefit analysis is often included in most recent models.	● Some key inputs have been often underestimated, and need a better representation in models, such as climate-induced pests and diseases, perennial tree crops (i.e. grapevine and hazelnut), potential shifts in diets along SSPs, impacts of single extreme events (such as hail or storm) and compound events, with consequent inter annual price fluctuations. ● A better understanding of the source of uncertainties. ● Regional differences need a better understanding both in biophysical and economic models, by accounting for robust regional land use patterns, non-adaptive supply chains with regional specialisation, and deriving region and sector specific exposure-response functions for heat stress impact. ● Representation of adaptation patterns and costs shall account for relevant rigidities in adaptation and the implication of proactive investments in mechanisation and R&D. ● Household dimension needs to be further assessed.
Forestry and fishery	The forestry sector has been studied quite consistently, especially in relation to wildfires and droughts. The study of the fishery sector shows a relevant degree of complexity because of multiple bio-chemical, climatic and economic interconnections. Drought impacts and costs do not show consistent gaps.	● Forestry: Non-monetary values and ecosystem services needs to be better implemented into cost benefit and cost-effective analysis, while adaptation strategies and relative potential costs and benefits needs to be further assessed, also focusing on increasing importance and frequency of wildfires hazard for economy and households ● Fishery: Cascade effects in marine ecosystems and large-scale effects of climate change on biodiversity need to be better understood, as well as effects on specific fish species. Adaptation strategies and aquaculture need to be better assessed. Future capture production shall be endogenously modelled.

Water management and droughts	The literature on drought impacts and relative costs for Europe seems to be well developed and does not show major gaps.	● Need to incorporate drought compound and cascading effects and their cross-sectoral and cross-national implications in future macroeconomic impact assessment at global and EU level. ● A better coverage on adaptation costs and possible EU strategies is needed.
River flood impacts	Good coverage at European, national and local level, especially for river floods direct expected annual damage (EAD) and indirect socio-economic impacts. Few data on costs and benefits of adaptation are present.	● Better understanding of model uncertainties is required. The natural variability of extreme events in predicting future trends imply significant differences in models' projections. ● Quality and quantity of the available observational data often prevent a good calibration of flood models, also accounting for spatial resolution and temporal dimension. ● Most hydrologic models do not consider the effects of a coevolution human-water system and the interactions between the hydrologic cycle with the human-economic system. ● Few studies systematically analyse impact and costs of different riverine adaptation measures and future projections. ● Local dimension of adaptation measures to reduce flood risks need to be better assessed and implemented into models. ● Household dimension and impacts on ecosystem services is often missing.
Coastal flooding and sea-level rise	Comprehensive coverage of coastal flood risk assessment, both from direct damages on infrastructures and indirect national and regional macroeconomic impacts at GDP level. Different levels of adaptation are often included when modelling its cost-effectiveness. Some improvements in coastal flood impact models are needed.	● Exposure to coastal flooding is often represented by simplified land-use classes, leading to an underrepresentation of heterogeneities in exposure. Including assets with higher resolution is needed. ● In assessing future impacts, an integrated, multi-hazard assessment mechanism is necessary to couple the impact of sea-level rise, longshore sediment transport and coastal erosion. ● Local dimension of adaptation measures to reduce flood risks need to be better assessed and implemented into models. ● Household dimension and impacts on ecosystem services is often missing
Impacts on Critical Infrastructures from multiple hazards	Increased understanding of compound and cascade effects from multiple hazards on Critical Infrastructures.	● Better understanding of impact on critical assets and infrastructure is needed, this requires better data on historical impacts of climate hazards, on different degrees of interconnectivity, technological heterogeneity, and the life span and vulnerability of specific infrastructures. ● Multiple hazards reinforce and overlapping, and cascade effects need to be better assessed. ● Better the quantification of vulnerabilities of various types of infrastructures/sectors to the different climate hazards. ● The building of new structures as a possible adaptation measure is not always considered, thus constituting a source of model uncertainty. ● The availability of observational relations linking variations in multi-hazard impacts on vulnerability is often scarce ● When accounting for extreme events such as windstorms and hail, few recent data and relevant research projects are present. ● High resolution exposure data is required to capture a large number of local adaptation assessments
Energy	Energy sector has been extensively studied relatively to his nexus with health, welfare and distributional implications. Different types of impact and energy systems have been studied, mostly on demand side and using many different models and research approaches; some relevant improvements from both modelling perspective and research focus need to be better implemented.	● Key elements need to be better included in future assessment, as structural changes in the economy (i.e. technological progress or improved efficiency), geopolitical changes, implementation of niche technologies, and the impact of extreme climatic events. ● Evaluation of compound impacts on the power systems with high-frequency projections need a better assessment in energy system models (i.e.simulating power dispatch and capacity expansion). Need to evaluate the implications of overlapping demand and supply side shocks on short-term system operations and long-term investments. ● The water-energy-food nexus should be further explored, as well as adaptation policy options. ● Relevant improvements from modelling perspective should account for spatial resolution of country-level annual data and better integration of supply-side impacts and climate-energy feedback into IAMs.

Tourism	In general, this sector appears to be poorly analysed, especially given the major importance of tourism for many European economies. Few recent economic impacts estimations are present.	● There are few recent economic estimations on climate impacts on tourism in Europe, both from demand and supply sides. ● Very little data is provided for winter tourism and more effort must be put on heat-related and wildfire impacts, especially for summer tourism. ● A better assessment is needed on ecosystem losses, sea level rise and losses of wildlife, in relation to tourism, as well as in understanding future tourists' preferences to develop better adaptation strategies. ● Demand models often rely only on temperature as a climate-related driver for tourism, with few studies incorporating composite tourist climate comfort indexes and adaptation options.
Business, industry, trade, and supply chains	Many studies have been carried on climate change impacts on industry, mostly assessing impacts of heat and floods on GDP aggregated level or labour productivity loss.	● Few studies assess the direct impact of extreme single events on industry/services. ● Other impacts beyond heat and floods need to be better assessed. ● Few estimations of labour productivity adaptation measures and costs are present. ● Analysis of spatial labour reallocation would deserve a deeper investigation, as well as increasing the sectoral detail of the econometric analysis. ● Apart from labour productivity, economic costs for trade and supply chains disruptions have not been widely considered. ● A gap still remains between the aggregation level of adaptation cost estimates performed by IAMs and CGE models, and the more precise, but not generalizable, local dimension of adaptation solutions. ● There is often a lack of granularity in providing impact assessments that focus on specific industrial sectors and accounting for adaptation.
Health	The main health impacts of climate change related to rising temperatures (mortality and impact on labour productivity) are quite well understood. Also a good coverage of related costs and adaptation is present.	● Some areas, such as vector-borne diseases and impacts on mental health remain understudied, but trends call for increased attention over the medium to long term. ● Projections are needed on a comparable basis for morbidity impacts. ● Projections of mortality and morbidity costs due to extreme heat in European countries should be refined to a more granular level for detailed welfare and budget assessments. ● Assessment of the needed supply of public health services to meet expected increases in health-treatment demand is crucial. ● Systematic evaluation of the effectiveness of early warning systems, increased air conditioning usage, and other adaptation options at a NUTS2 level is still necessary. Evaluation of adaptation effectiveness, considering differences in available resources at the household level, for different classes of households, requires further attention.
Biodiversity and ecosystems	Although the climate impacts on biodiversity are well quantified, the specific economic impacts of biodiversity loss are generally hard to exactly quantify. These are commonly estimated either by assuming that there is an existing market or demand for certain ecosystem services, or estimating the current and added economic costs of conserving biodiversity.	● The economic implications of biodiversity change remain poorly understood and quantified from almost every point of view. ● Little to no data is openly available on the costs and impacts of European nature conservation efforts. ● Benefits of climate adaptation are not aligned with biodiversity conservation objectives. ● Current biodiversity impact models tend to focus on the broad-scale implications of climate change, and less on sub-annual climatic extremes (fires, droughts, etc). ● How and where biodiversity should be managed under different European climate pathways (mitigation or adaptation) is not clear.
Social justice and distributional implications	Methodologies to assess the social justice dimensions of adaptation policy are only recently beginning to emerge. In terms of quantitative analysis, until now the literature has offered few quantifications of the heterogeneous vulnerability of EU citizens, but mainly focuses on the distributional implications of mitigation policies.	● Considerable gaps in the evidence base about the effectiveness of initiatives to address changing vulnerabilities and respond to the differential effects of adaptation. ● Need for more empirical evidence on the impacts of adaptation policies on marginalised groups, intersectionality of climate justice issues, and the development of practical tools for assessing and implementing social justice principles within policy frameworks. ● The impact on households is in general disregarded and so is the distribution across household types. ● The empirical literature is still narrow and usually sector-, commodity-, and region/country specific.

Financial and fiscal implications	While there is a vast body of literature on the role of the insurance sector, literature on the role of financial markets as transmitters of physical climate risks is still comparatively limited, at least in terms of modelling.	● Better assess the welfare benefits of different types of adaptation beyond infrastructure investment, such as early-warning systems, heat action plans, nature-based solutions etc. ● Soft and hard limits of adaptation options for different RCP-SSP combinations, replacing the default assumption of uniform damage reduction potentials ● Different adaptation intensities (keeping expenditures constant or expanding it; keeping protection levels constant), e.g. also reflective of different SSP narratives. ● The sustainability of risk sharing mechanisms across European countries (Solidarity Fund), considering compound risks and feedbacks to government budgets. ● Stress testing of government budgets, considering that governments are providing assistance of last resort to households and companies ● Assessment of fiscal implications at lower governance levels (provincies/states; municipalities).
Socio-economic tipping points	While recent studies have better defined possible socio-economic tipping points for European society, the relative literature appears quite new and many important key elements need to be further assessed.	● There is very low coverage on adaptation costs and strategies when it comes to tipping points. ● Few estimates are present of economic costs in case of SETPs. ● Few efforts have been done in disentangling the "average" climate change impacts and the tipping point scenario in future impact assessment. ● The insurance market in case of SETPs scenario deserves more attention, in particular at household level. ● Deeper focus is needed on social aspects as health, poverty, labour productivity, living conditions in cities and rural areas

PART II: SCENARIO FRAMING

Analysis of the future impacts and economic costs of climate change uses models and scenarios. Scenarios provide a description of how the socio-economic systems may develop over the 21st century, based on a coherent and internally consistent set of assumptions about key drivers including demography, economic processes, technological innovation, governance, lifestyles, and relationships among these driving forces (IPCC, 2021; Rounsevell and Metzger, 2010; O'Neill et al., 2014).

12. Socio-economic scenarios: a review of their development and use

One consolidated way to deal with the climate and socio-economic uncertainty that characterises any climate impact assessment is the use of scenarios. Scenarios are plausible, coherent, internally-consistent descriptions of how the future might develop based on consistent assumptions, in a context of complex causal relationships, limited knowledge, and high uncertainty. According to Börjeson et al. (2006) scenarios can be classified based on what type of question about the future they are designed to answer:

Predictive scenarios respond to questions of the type: What *will* happen in the future?

Explorative scenarios respond to questions of the type: What *can* happen in the future?

Normative scenarios respond to questions of the type: What *should* happen in the future?

Following Börjeson et al. (2006), explorative scenarios in turn can be divided into external and strategic scenarios. The former describe possible developments in factors that are *beyond the control of the decision-maker*. The latter respond to questions of the type: What can happen if we act in a certain way? They describe how the consequences of policy decisions and other strategic decisions can vary depending on how the future evolves.

IPCC scenarios can thus be placed in the **explorative category**. More precisely they are defined as: "coherent, internally consistent, and plausible description of a possible future state of the world" (Carter, La Rovere). They are thus **narratives** offering alternative views of future conditions considered likely to influence a given system or activity. In the IPCC process, a distinction is made between climate scenarios — which describe the forcing factor of focal interest to the Intergovernmental Panel on Climate Change (IPCC)— and non climatic scenarios, which provide socioeconomic and environmental "context" within which climate forcing operates.

The importance of scenarios has been central since the initial phases of the IPCC activity. However, the first structured effort in scenario production coupling climatic and economic drivers is the release of the Special Report on Emissions Scenarios (SRES) in 1999 (Nakicenovic et al. 2000) to replace the earlier set of six IS92 scenarios developed for the IPCC in 1992. The SRES centred on a group of social-economic scenario families (called A1, A2, B1, B2) presenting four qualitative descriptions of the future, from the more "brown" to the more "environmental or sustainability friendly". To each family, and declinations within family, a given path of GDP, population, and emissions were associated. The SRES proved to be useful in offering a first consistent and shared context to investigate climate change impacts and policies, with the non-marginal benefit to provide a linkage across social-economic sciences and climate sciences. This connection was initially "linear". Simplifying: the different social economic development paths would determine GHG emission profiles that then climate scientists translate in temperature increase through climate models. In the last step, environmental and economic damage could be associated with temperature paths. The SRES scenarios were strictly "no policy scenarios". Nonetheless, the SRES scenarios also raised many criticisms (Grübler et al., 2004; Wang et al., 2017). The most relevant for the current report, refers to the quite rigid structure imposed by the linear interpretation of the linkages across socio-economic, read GDP growth, and emission profiles. It was noted that the quality of development, given population and GDP growth, can produce very different emission, CO2 concentration and radiative forcing profiles or, symmetrically, that the same radiative forcing can stem from quite different population and GDP growth paths.

The *Shared Socio-Economic Pathways* - *Representative Concentration Pathways* (SSP-RCP) framework was then developed to inform IPCC AR5 and AR6. The *Shared Socio-Economic Pathways* (SSPs) (O'Neill et al., 2017; Riahi et al., 2017) characterise the future evolution of the world depending on socioeconomic development, technological advancements, policy decisions, and global cooperation. They consist of two main elements: a set of qualitative, narrative storylines describing societal futures (O'Neill et al., 2017) and a set of quantified measures of development at aggregated and/or spatially resolved scales (IPCC AR6, 2021). The SSPs, see Table 1.A differ in terms of the socioeconomic challenges they present for climate change mitigation and adaptation (Rothman et al., 2014; Schweizer and O'Neill, 2014). These narratives (Riahi et al, 2017; O'Neill at al., 2017) range from SSP1 to SSP5, providing an internally consistent, plausible and integrated description of a socio-economic future, but they do not account for the effects of climate change and climate policies implementation (IPCC AR6, 2021).

Table A | Main features of the SSPs.

SSP	Challenges	Key elements
SSP1	Adaptation: low Mitigation: low	**Sustainability**: Sustainable development, low inequalities, rapid technological change directed toward environ-mentally friendly processes, high productivity of land
SSP2	Adaptation: moderate Mitigation: moderate	**Middle of the Road**: A continuation of current trends, intermediate between all other scenarios
SSP3	Adaptation: high Mitigation: high	**Regional Rivalry**: Moderate economic growth, rapidly growing population, slow technological change in the energy sector. High inequality, reduced trade flows, unfavorable institutional development, leaving large numbers of people vulnerable to climate change
SSP4	Adaptation: high Mitigation: low	**Inequality**: A mixed world, with relatively rapid technological development in low carbon energy sources in key emitting regions. In other regions, development proceeds slowly, and therefore inequality remains high
SSP5	Adaptation: low Mitigation: high	**Fossil-fuel Development**: Rapid economic development and high energy demand, most of which is met with carbon-based fuels. Low investments in alternative energy technologies. More equitable distribution of resources, stronger institutions, and slower population growth

Source: Our elaboration

Representative Concentration Pathways (RCPs), are used to describe different **pathways of GHG emissions** (Figure 2), atmospheric concentrations, radiative forcing (W/m^2), temperature, air pollutant emissions and land use for the 21st century. The RCPs do include climate policies: a stringent mitigation scenario consistent with global warming likely below 2°C above pre-industrial temperatures characterises RCP2.6, no mitigation policy is assumed for the RCP8.5. Other RCPs are in between (see Table B) .

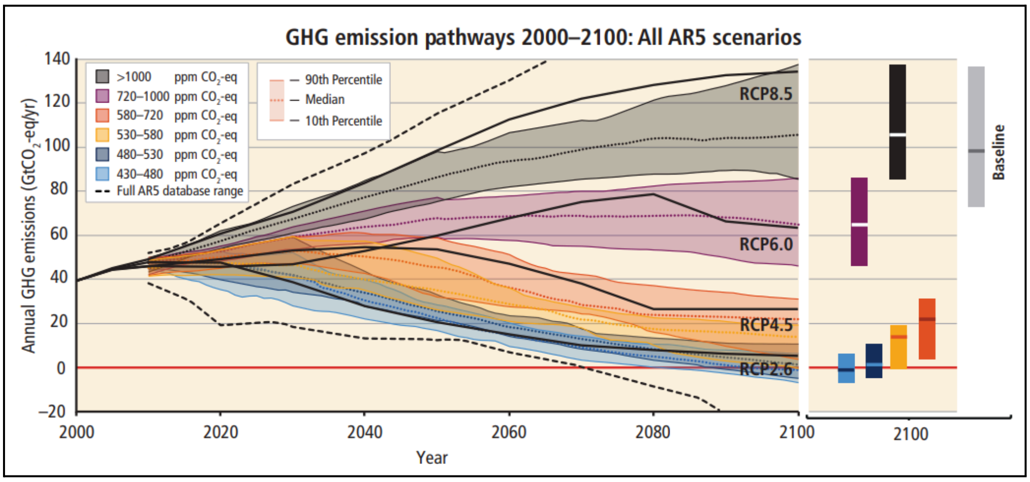

Figure 2 | Emission from different RCPs
Source: IPCC AR5, SPM (2014).

Table B | Main features of the RCPs. Radiative forcings in W/m2 are in RCPs names

Scenario Component	RCP2.6	RCP4.5	RCP6.0	RCP8.5
Average temperature change in 2100	Well below 2 °C	2.5 °C	More than 3 °C	4.5 °C
Greenhouse gas emissions (relative to 1850/1900)	Very low	Medium low	Medium	High
Mitigation effort	Aggressive mitigation	Medium-high mitigation	Medium-low mitigation	Virtually No mitigation

Source: Our elaboration

The major novelty compared to the SRES exercise consisted in the production of a **matrix approach** (see Figure 3) where multiple combinations across SSPs and RCPs are considered plausible with quite few judged "unfeasible" on the basis of the difficulties by Integrated assessment Models (IAMs) to replicate them. This offered more flexibility to both social and climate scientists to examine a richer combination of "futures". The framework was also designed to bridge the gap between climate impact modelling and mitigation assessments to facilitate further integration through the use of a common scenario setup. Within this context an important role was played by "Shared climate policy assumptions" (Kriegler 2014) that capture key policy attributes such as the goals, instruments and obstacles of mitigation and adaptation measures, and introduce an important additional dimension to the scenario matrix architecture.

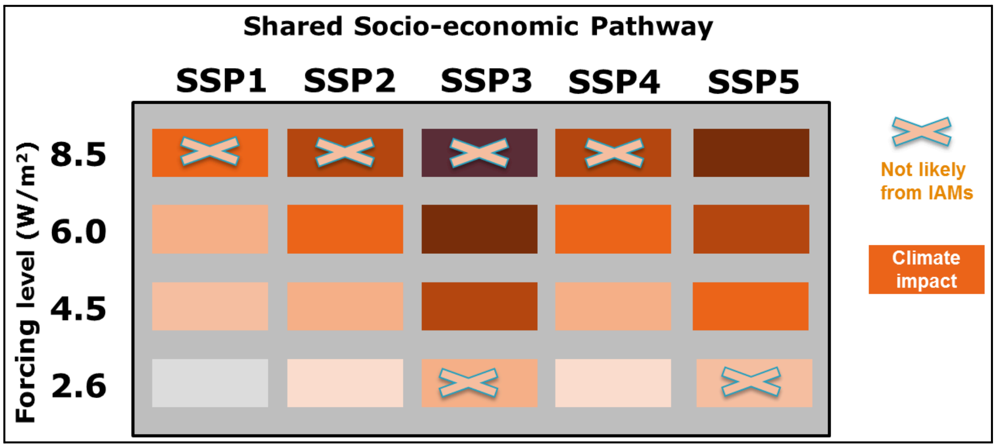

Figure 3 | Feasibility of alternative forcing agents across the SSPs.
Source: our elaboration based based on Riahi et al. (2017)

This framework provides now the most widely used set of scenarios in the climate change literature[15] (Tröltzsch et al., 2018; O'Neill et al., 2020).

BOX 12A. The use of the SSPs-RCP framework in the COACCH project

Within the COACCH (Co-Designing the Assessment of Climate Change Costs, Grant Agreement No 776479) H2020 project, precursor of ACCREU, 9 combinations arising from the association of four Shared Socioeconomic Pathways (SSPs) and four Representative Concentration Pathways (RCPs) have been selected (see Table C). At the two extremes the project analysed the sustainability - low climate change combination of SSP1-RCP2.6 and the fossil based high climate change combination of SSP5-RCP8.5.

[15] For a broad introduction about the historical development of the scenario framework see: IPCC AR6, 1.6.1.3, pp. 237.

Table C| Selected scenario combinations used in the COACCH project

	RCP2.6	RCP4.5	RCP6	RCP8.5
SSP1 (Green Growth)	✔	✔		
SSP2 (Middle of the road)	✔	✔	✔	
SSP3 (Regional rivalry)	✔	✔		
SSP5 (Fossil fuel development)		✔		✔

In the choice of the relevant combinations, **ACCREU stakeholders' role was prominent**. Following their indications **SSP2-RCP2.6** and **SSP2-RCP4.5** were regarded as the central scenario combinations in the project. To capture additional important sources of uncertainty, the RCP dimension has been quantified with input from different climate models presenting "low" and "high" climate signals, while on the socioeconomic side sensitivity analyses on key social economic parameters like the degree of trade openness and of international mobility of investment were conducted.

The SSP-RCP framework is not static. It is in constant evolution capturing novel aspects and dynamics that can emerge as essential determinants of the climate challenge and its solution. In this vein Leimbach et al., (2023) extended the SSPs with the evolution of the sectoral structure of economies as a driver of energy demand and, more in general, as an important influencing factor of climate change impacts and of mitigation policies. Other missing aspects in the original SSPs such as digitalization, fisheries, agriculture, conflict have led to the development of extensions, interpretations, and the development of new knowledge that can be included in the next generations of community scenarios (van Ruijven et al., 2022).

Similarly, social and economic trends characterising the SSPs are not fixed, but are updated to reflect evolving conditions and new knowledge. For instance, Koch and Leimbach, 2023, offer a major update of the SSP's GDP projections and population levels still compatible with the SSP narratives, but reflecting also new and most recent evidence. Currently, the SSPs economic projections are being updated by The International Committee on New Integrated Climate Change Assessment Scenarios (ICONICS) considering the latest demographic and economic data and most recent research on the topic.

BOX 12B. Relevant sources of uncertainty under climate change

As for IPCC AR6 the use of different scenarios for climate change projections allows the exploration of 'scenario uncertainty' (IPCC AR6 Section 1.4.4; Collins et al., 2013). Scenario uncertainty is fundamentally different from uncertainties in the understanding and predictability of the climate system (Smith and Stern, 2011). In scenarios, future emissions depend to a large extent on the collective outcome of choices and processes related to population dynamics and economic activity, or on choices that affect a given activity's energy and emissions intensity (Jones, 2000; Knutti et al., 2008; Kriegler et al., 2012; van Vuuren et al., 2014). Even if identical socio-economic futures are assumed, the associated future emissions still face uncertainties, since different experts and model frameworks diverge in their estimates of future emissions ranges (Ho et al., 2019).

Another relevant source of model uncertainty may be related to emission-induced climate feedback. As described in the present chapter, the SSPs-RCPs framework is labelled to estimate the level of radiative forcing the Earth system would reach in 2100, yet there is an **uncertainty component** in the carbon cycle response to climate change and in assessing the **time dimension** on which main physical impacts occur. The links between the time in which different warming levels are reached and the corresponding greenhouse gas concentration pathways to reach them remain poorly understood (Mentaschi et al., 2020).

Moreover, while for many climate variables the response pattern for a given global mean temperature change has been found to be consistent across different scenarios and almost-linearly related to a number of **regional climate effects** (Mitchell et al., 2000; Mitchell, 2003; Tebaldi and Arblaster, 2014; Seneviratne et al., 2016; Li et al., 2020; Seneviratne and Hauser, 2020), the regional and sub-national response to different emissions scenarios still may represent a source of uncertainty, being related to regional climate sensitivity (Seneviratne and Hauser, 2020).

The regional and sub-national dimension of climate change imply an increasing need for climate data and impact models to support decision-making for local **adaptation policies** under deep risk uncertainty (Ciullo et al., 2021).

When assessing climate change risks, interactions among multiple hazards need to be accurately evaluated as a source of model uncertainty, since new evidence shows that interactions across numerous sectoral, regional, and response-option boundaries strongly influence some of the most severe climate change effects (Simpson et al. 2021). Addressing hazards separately can lead to inaccurate response-plans that miss the complexity of climate change risks since adverse impacts are usually caused by multiple hazards that can then lead to cascading effects. Compound and cascading natural hazards usually cause more severe impacts than any of the single hazard events alone (Sutanto et al., 2019). For example, crop failure commonly is induced by the occurrence of multiple and combined anomalous meteorological drivers (Goulart et al., 2021).

Assessment of impacts resulting from remote climate change features requires an analysis framework that embraces a "systemic risk" approach (Hochrainer-Stigler et al., 2020) and acknowledges complex interactions between risk attributes, including system boundaries, socio-economic vulnerability, long impact transmissions, relevant climate features, the risk propagation mechanism, quantitative hazard impact evaluation, and specification of alternative scenarios (Carter et al., 2021).

Interdisciplinary analytical and modelling approaches are thus required to account for the large complexity and uncertainty of impact chains, and the conventional probabilistic approach of modelling uncertainty in regional climate (generating local climate information by downscaling results from global climate model ensembles simulations), has been often criticised when accounting for actionable risk perspective (Hazeleger et al., 2015, Shepherd et al., 2018, Shepherd, 2019, Sillmann et al., 2021).

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13. IPCC AR6 "revisiting" the Shared Socio-Economic Pathways

The IPCC AR6 thus uses a core set of five illustrative SSP-RCP scenarios (SSP1-1.9, SSP1-2.6, SSP2-4.5, SSP3-7.0 and SSP5-8.5) to span a wide range of plausible societal and climatic futures from potentially below 1.5°C best-estimate warming to over 4°C warming by 2100 (Figure 4).

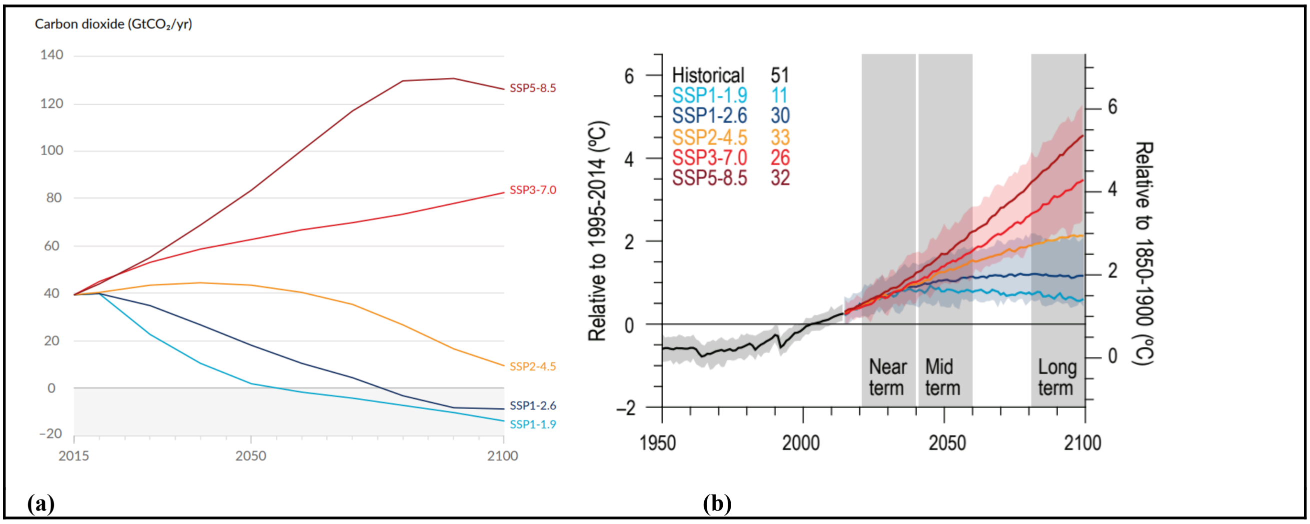

Figure 4 | Annual CO_2 emissions (a) and relative global surface air temperature changes (b) for selected SSP-RCP combinations. Source: IPCC AR6, 2021, pp. 571 (a) and pp. 13 (b)

The five core scenarios were used mostly by WP1 in order to simulate a range of plausible societal and climatic futures, from potentially below 1.5°C best-estimate warming to over 4°C warming by 2100. IPCC WGIII explored a much wider range of possible emission scenarios, reflecting different assumptions about demography, economic development, technological innovation, governance, lifestyles, institutions and policies. These scenarios are called **Illustrative Mitigation Pathways (IMPs)** and they explore different pathways, reflecting different mitigation strategies affecting the energy system and emission pathways (Figure 5).

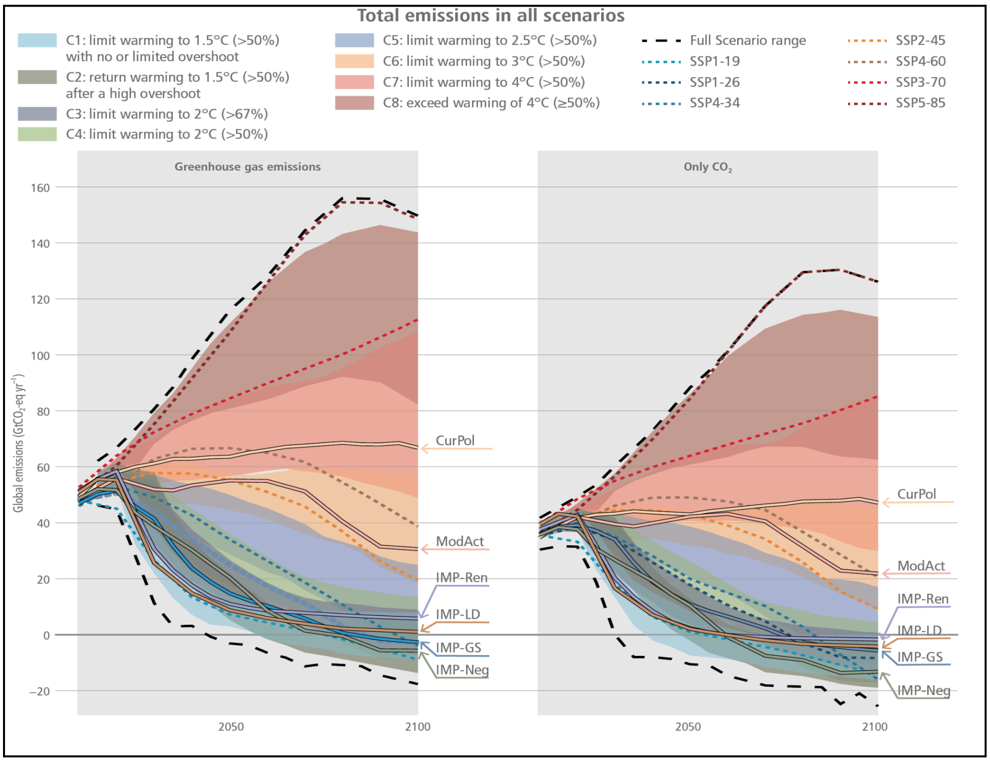

Figure 5 | Total emissions profiles for scenarios, based on climate category for GHGs (AR6 GWP-100) and CO2. Source: IPCC AR6 WGIII, Climate Change 2022 Mitigation of Climate Change, 2022.

Two reference pathways, Current Policies (CurPol) and Moderate Action (ModAct), explore the consequences of current policies and pledges. The CurPol pathway explores the consequences of continuing along the path of implemented climate policies in 2020 and only a gradual strengthening after that. The ModAct pathway explores the impact of implementing the Nationally Determined Contributions (NDCs) as formulated in 2020 and some further strengthening after that. Current policies lead to median global greenhouse gas (GHG) emissions of 57 GtCO2-eq with a full range of 52–60 by 2030. NDCs with unconditional and conditional elements lead to 53 (50–57) and 50 (47–55) GtCO2-eq, respectively. When conditional elements of NDCs are included, these gaps narrow to 16–23 GtCO2-eq and 6–14 GtCO2-eq, respectively. The IMPs differ in terms of their focus, for example, by placing greater emphasis on renewables (IMP-Ren), deployment of carbon dioxide removal that results in net negative global GHG emissions (IMP-Neg), and efficient resource use and shifts in consumption patterns, leading to low demand for resources, while ensuring a high level of services (IMP-LD). Other IMPs illustrate the implications of a less rapid introduction of mitigation measures followed by a subsequent gradual strengthening (IMP-GS), and how shifting global pathways towards sustainable development, including by reducing inequality, can lead to mitigation (IMP-SP).

14. The global warming levels (GWLs) approach

Another scenario approach has been proposed by the literature to mostly address the issue of climate uncertainty that pertains to the relationship between CO2 concentrations and temperature increases. This approach assesses climate impacts for a specific Global Warming Level (GWL), independently on the underlying possible socioeconomic pathways. Some recent studies adopted this perspective, analysing the effects of reaching alternative global warming levels (GWLs) independent of specific socio-economic scenarios of future emissions. For instance comparing impacts in the GWL range consistent with the Paris Agreement, against those characterising higher GWL (Tebaldi et al., 2021). Dottori et al., (2023) apply a

GWL approach to study the evolution of river streamflow under climate change. Future flood exposure and impacts were then derived without the use of SSPs, but combining regional flood projections and European socioeconomic projections based on historical trends, ageing and migration flows.[16]

15. Socioeconomic scenario modelling: key gaps and considerations

Key improvements from scenarios framing perspective:

- Some suggestions underline the increasing importance of SSP3, and the need for implementing sensitivity analysis regarding climate models and adaptation for this scenario. In addition to the present (and possibly worsening) degraded geopolitical situation, there are also some interesting suggestions from impact studies.[17]

- The feedback of climate impacts on the underlying SSP pathways, as well as the interaction with the mitigation dimension, is under-researched. SSP baseline scenarios with climate impacts might already provide a very different starting point for mitigation assessments.

- While the SSP-RCP framework has been extensively used to assess climate change impacts and mitigation policies, adaptation has been analysed within a lesser extent. There is also room for further developing specific climate policy scenarios related to the Shared Climate Policy Assumptions as described in Kriegler et al (2014), in particular with a focus on adaptation policies.

-The implementation and quantification of the role of climate change adaptation in different scenario-building exercises is still less developed and consolidated than that of climate change mitigation. These are all areas of research that deserve more effort and that can benefit the socio-economic modelling community.

- The use of the SSP-RCP framework for adaptation assessment studies have mostly focused on sea-level rise (Reimann et al., 2023; Lincke, D., & Hinkel, J., 2021; Hinkel et al., 2015) and river floods (Ward et al., 2017) with fewer studies at the macroeconomic level (Bachner et al, 2022; Bosello et al., 2020; Parrado et al., 2020)[18].

- Some efforts shall be taken to include possible effects and severeness of conflicts and migrations into the SSPs-RCPs framework, as different pathways imply different geopolitical impacts on global economies and distributional implication across the global population.

- Similarly, further research needs to include different levels of ecosystem degradation and biodiversity loss into the scenario framework, as these elements may be drivers of conflicts, migration and welfare loss.

- Strong extreme events or other rare high risk tipping points (but also pandemics) are ignored in the smooth projections of the SSPs and would have an effect even without additional climate change.

[16] They consider future climate scenarios corresponding to an increase in global average temperatures of 1.5, 2 and 3 °C. Projections of river streamflow with global warming are based on regional climate EURO-CORDEX projections for RCP 4.5 and RCP 8.5 and are used to generate daily streamflow simulations and floodplain inundation processes with LISFLOOD-FP model. Exposure information are derived from the European population density map from Batista e Silva 2018, and the refined version of the CORINE Land Cover proposed by Rosina et al, 2018. Socioeconomic projections are based on the ECFIN 2015 Ageing Report that includes GDP and population projections. High-resolution population projections are derived by the LUISA modelling platform (Jacobs-Crisioni et al., 2017) capturing the fine-scale processes of population dynamics (for example, urban expansion, stagnation or de-growth) and concentration that represent key drivers of the future exposure of populations.

[17] In the case of labour productivity, for example, Bosello et al., 2020, show that, despite the climate change projections exerts a larger importance than the social economic scenario in the determination of short to mid-term macroeconomic impacts, the SSP3 scenario, featuring lower “flexibility” in the energy production process and in trade mechanisms, tends to highlight higher GDP losses than other SSPs.

[18] While the macroeconomic assessment from the COACCH project included market-driven (or autonomous) adaptation, the only impact that included “planned” adaptation scenarios was sea-level rise, which also allowed to produce regional damage functions with current adaptation and with increasing adaptation to sea level rise (van der Wijst et al., 2021). However, the adaptation scenarios were only assessed for a subset of SSP-RCP combinations (Bosello et al., 2020). Moreover, a substantial amount of risk literature uses different scenarios or does not draw on scenarios (van Ruijven et al., 2022).

- When accounting for local climate events inducing cascade effects and multiple hazards, future work must homogenise the available analytical approaches into a robust toolset for compound-event analysis under present and future climate conditions (Zscheischler et al., 2020). In this, the physical climate storylines approach is proposed to explore complex impact transmission pathways and possible alternative event cascades under future climate conditions (Ciullo et al., 2021) as an alternative to probability-based approach.

Key improvements in data availability and modelling perspective:

- When it comes to exposure analysis, the availability of better socio-economic data projections is often required for the development of future scenarios.

- The Shared Socio-economic Pathways (SSPs) relating to GDP and population growth are specified at the "country level", and for most research the sub-national disaggregation is missing, which makes them less applicable for impact and adaptation analyses at regional to local levels.

- Even if an increasing number of initiatives provide "downscaled" or gridded specification of SSPs (for instance Murakami and Yamagata 2016), there is no commonly agreed best practice regarding methods for downscaling the global SSPs (O'Neill et al., 2020).

- Regarding adaptation studies, most socio-economic vulnerability data (i.e., related to sensitivity and adaptive capacity), including demographics, income and gender, are needed at the sub-regional scales (regional, provincial or municipal administrative levels) (Ebrey R. et al. 2021)[19] .

- Some issues about SSPs scenarios framework update have to be taken into consideration, given that upward revisions of GDP and other economic parameters can dominate IAMs results (Nordhaus, 2017a). O'Neill et al. (2020) identify needs and opportunities for improvement of the SSP framework, i.e. the necessity to keep the scenarios up to date[20].

- A further translation of the broad SSP narratives into regional and sectoral narratives and specification, as well as additional elements of quantification would increase the uptake of the framework. In particular a better quantification of the "adaptation challenge" axis would be important to reflect it in integrated assessment modelling. The recently put forward adaptive capacity approach (Andrijevic et al. 2023) is a useful step in this direction.

We overall underline the need for a careful evaluation of the scenario framework, especially accounting for possible cascade effects between different hazards, sectorial interconnections at European level, scenario-dependent probability of incurring in tipping points and possible deglobalization pathways. The possible different impacts of war, migrations and biodiversity and ecosystem loss may be implemented within the SSPs-RCPs framework. Moreover, the literature has shown the importance of local and sub-regional storylines for adaptation, beyond the scenarios downscaling approach.

16. Framing ACCREU's scenario

The primary objective of ACCREU's scenario framework is to investigate the possibilities for adaptation under that climate outcome and assumed societal conditions, and the remaining impacts on society or ecosystems. ACCREU's scenarios have been selected within the updated SSP-Radiative Forcing Matrix displayed in Figure 6. ACCREU consortium decided to focus on one SSP, namely the middle-of-the-road socio-economic scenario, which extrapolates to the future the historical trends. Considering the primary objective of ACCREU - characterise the possibilities of adaptation and residual damages - three scenarios of varying forcing levels have been considered. A low warming scenario, 2.6, leading to 2 degree warming in 2100 relative to 1850-1900; a moderate warming scenario, 4.5, that aligns with the IMP ModAct implementing the NDCs as formulated in 2020 and leading to 2 degree warming relative to 1850-1900 in

[19] While most of the social-economic indicators typically used to measure sensitivity and partly adaptive capacity in Europe are available either at NUTS2 or sometimes at NUTS3 administrative levels, to perform analysis on finer resolutions developers have to either use the countries' census data (Marzi et al., 2019), or perform statistical downscaling based on proxies, as in Amadio et al. (2018), or consult stakeholder-driven approaches (Linkov and Trump, 2019).

[20] An update is provided by Koch and Leimbach, 2023. .

2040 and 3 degree in 2100; a higher warming scenarios, 7, which has higher emissions compared to current policy scenarios, and is used a reference scenarios without mitigation for the the analysis of climate change impacts (4 degree warming in 2100 and about as 2.5 in 2040).

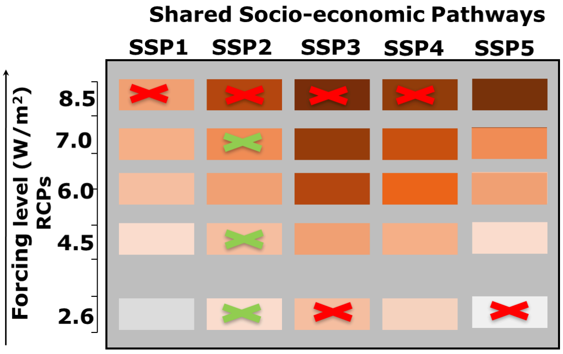

Figure 6 | Feasibility of alternative forcing agents across the SSPs. Source: Own elaboration based on Riahi et al. (2017). Green crosses mark the ACCREU scenario

Additional considerations that justify the ACCREU's choice of scenarios include the COACCH results that most variation in climate impact results come from models and climate uncertainty, while socio-economic assumptions do not lead to significantly different climate impacts. The ACCREU's scenario approach was presented during the First Stakeholder Workshop on January 10th in Brussels. Stakeholders point out the importance of considering variations in socio-economic assumptions as well, especially considering the novel focus of ACCREU on adaptation, its efficacy, but also its feasibility and limits. During the First Stakeholder Workshop, it was discussed to develop some adaptation scenarios, starting from the core socio-economic development trajectories of SSP2, and considering variations in important variables that influence adaptive capacity (Andrijevic et al. 2023). The actual implementation will be driven by the specificities of the model but a number of broad adaptation narrative and storylines will be considered. Adaptation narratives will also be informed by Work Package 3, which will develop the Adaptation Decision Type case studies. Table D illustrates examples of narratives that could stem from WP3.

Table D| Example of illustrative adaptation storylines

Strategic pathways	**Adaptation Mission Key Community Systems** / *ACCREU decision types*				
	Water management *Regional adaptation (flood risk management)*	**Ecosystems and nature-based solutions** *Sustainable Forestry*	**Health and wellbeing** *Health and social justice in regional and urban adaptation*	**Infrastructure** *Resilient transport infrastructure*	**Agriculture and food security** *Integrated adaptation decisions in managing the water-food-biodiversity*
VULNERABILTY REDUCTION	Flood proof building, Disaster preparedness, flood insurance	increase heterogeneity; promote new climate resilient species	heat alert system, public drinking water taps		drought resistant crops, diversification of rural economy
EXPOSURE REDUCTION	Zoning, spatial planning, managed retreat	Restrict human activity in near/forest	cools spots, white surfaces, increase shading	drainage systems, risk-based planning	shading nets, drip irrigation, eflow enforcement
HAZARD REDUCTION	Upstream Retention, increase infiltration, Room for rivers, Flood protection, surge and wave reduction, flood control infrastructure, SuDS, wetlands	Make corridors	Greening the cities		Large scale upstream water retention
ADAPTIVE CAPACITY / ENABLING ENVIRONMENT	Improve integrated flood risk governance; Increase risk awareness of citizens	Capacity building among practitioners, Fire response planning	Include adaptation against heat, vector-borne diseases and floods into urban development		New business models for farmers. Nature-inclusive landscape management. IWRM, watershed management
MITIGATION	Carbon capturing; reforestation, mangroves, hydropower	Reforestation	Cooler cities require less energy for cooling. Greening		

During the Stakeholder meeting, stakeholders from the European Investment Bank pointed out the Network for Greening the Financial System (NGFS) scenarios. This is an additional set of scenarios and visions that contribute to the development of climate and environment-related risk management in the financial sector. These scenarios reflect the latest GDP and population pathways and the most recent country-level commitments until March 2023, as well as the more disorderly future. They cover the physical risks of drought, heatwaves, floods, and cyclones, as well as different futures of climate action. NGFS are also organised in a matrix, as is the SSP-RCP framework. While the SSP-RCP framework conceptualises scenarios with respect to mitigation and adaptation challenges, the NGFS scenarios are framed more from the viewpoint of an investor concerned with physical and transition risk. Physical risk can be mapped into the challenges for adaptation while transition risk can be mapped into the challenges for mitigation.

ACCREU will also use the updated scenarios that are being developed by the modelling community and that are available from the IIASA repository https://iiasa.ac.at/models-tools-data/ssp. Input data on climate variables will be taken from the ISIMIP initiative for the forcing scenarios 2.6 and 7, (ISIMIP3b, GCM-based quantification of impacts at different levels of climate change). Another source of climate data will be Downscaled Climate Projections (NEX-GDDP-CMIP6) from NASA.

During the workshop we also received feedback on the issue of uncertainty and the issue of the time horizon of the analysis. Related to this is the key issue of **uncertainty**, which is critical to the analysis of climate change and especially adaptation. The first uncertainty issue is around the GHG emission pathway that will emerge and whether the world will warm by 2˚C, 3˚C or 4˚C relative to preindustrial levels. This can be considered by looking at multiple scenarios (RCPs). A further uncertainty factor is the difference in the results from various climate models, both from the GCMs and the RCMs. These often involve very large differences, for example, between hotter or cooler, or wetter and drier models. This will be considered by sampling different climate models across the ensemble. Regarding the **time horizon**, policy makers have a stronger interest in the historical period and the short term, 2030. Scenarios tend to be more long-term, and analyses tend to focus on 2050 and 2100. As ACCREU will be targeting users both in the scientific and policy domain, all three time slots, 2030, 2050 and 2100 will be considered.

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Appendix A: Recap of the State of Knowledge for COACCH and ACCREU

State of Knowledge as for COACCH D1.2 (2018)			As for ACCREU D1.1 (2023)	
Risk / Sector	**Coverage of Economic Analysis / Policy**	**Cost Estimates**	**Achieved knowledge improvements**	**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).	✓ ✓ ✓	Consistent improvements in coastal flood risk assessment, both from direct damages on infrastructures and indirect national and regional macroeconomic impacts at GDP level. Different levels of adaptation are often included when modelling adaptation's cost-effectiveness.	✓ ✓ ✓
Floods including infrastructure	Good coverage at European, national and local level, especially for river floods (less so urban). Applied policy studies including adaptation / DMUU.	✓ ✓ ✓	Good coverage of both direct expected annual damage (EAD) and indirect socio-economic impacts. Increased understanding of compound effects from multiple hazards on Critical Infrastructures.	✓ ✓ ✓
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	✓ ✓	Good level of spatial and temporal resolution of both productivity and bio-economic models. Much research focuses on wide economic sector impacts or aggregated damages across countries. Some recent models include adaptation strategies and relative cost-benefit analysis.	✓ ✓ ✓

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.	✓✓	Very good coverage of impacts from heating and cooling on energy demand, also as autonomous adaptation solution in residential sector. Consistent improvements in energy production assessments from both renewables and fossil fuel.	✓✓✓
Health	Good coverage of European and national heat-related mortality. Some estimates for food-borne disease. Lower coverage for other impacts. Emerging evidence based on adaptation policy (heat).	✓✓	The main health impacts of climate change related to rising temperatures (mortality and impact on labour productivity) are quite well understood. Also a good coverage of related costs and adaptation is present.	✓✓
Transport	Some European studies on road and rail infrastructure (extremes). Limited studies for air and indirect effects. Limited adaptation policy analysis.	✓✓	Consistent improvements in assessing impacts on Critical Infrastructures, including transports, from multiple hazards. Overall good coverage of economic disruption due to transport sector impacts.	✓✓✓
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.	✓✓	Few recent knowledge improvements are present, especially given the major importance of tourism for many European economies. Few recent economic impacts estimations are present.	✓
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.	✓	Good coverage of productivity and aggregated bio-economic impacts on forestry and fire hazard. Some key improvements in marine fishery production and macroeconomic impacts.	✓✓
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.	✓	The literature on drought impacts and relative costs for Europe has been widely improved and does not show major gaps. Adaptation costs and cascading effects need a better assessment.	✓✓
Business, services and industry	Low evidence base of quantitative studies. Some studies on labour productivity. Limited analysis of economic impacts on supply chains.	✓	Many studies have been proposed on climate change impacts on industry, mostly assessing impacts of heat and floods on GDP aggregated level or labour productivity loss. Impacts on national and international trade and supply chain, as well as cross-border impacts have also been assessed.	✓✓
Macroeconomic analysis	Several pan-European studies using CGE models. Low coverage of effects on drivers of growth, employment, competitiveness.	✓	Good to very good coverage of macroeconomic implications from different climate change impacts.	✓✓✓

Biodiversity and ecosystem services	Very low evidence base on economic impacts. Adaptation policy studies limited (only restoration cost studies).	⊗	The climate impacts on biodiversity are better quantified; the specific economic impacts of biodiversity loss are generally hard to exactly quantify. The economic implications of biodiversity change remain poorly understood and quantified from almost every point of view.	⊗
Climate tipping points	Some studies of economic costs of major sea level rise in Europe (>1m). Low economic coverage on other bio-physical climate tipping points.	✓ / ⊗	Literature on climate tipping points at European level still appears to be quite scarce, in particular when assessing adaptation options and cost estimations.	✓ / ⊗
Social-economic tipping points	Emerging interest in socio-economic tipping points (migration, food shocks) but no economic analysis.	⊗	While recent studies have better defined possible socio-economic tipping points for European society, the relative literature appears quite new and many important key elements need to be further assessed.	⊗

✓✓✓ = High coverage. ✓✓ = Medium coverage. ✓ = Low coverage. ⊗ = Evidence gap.