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Climate change impacts and adaptation in Europe

JRC PESETA IV final report

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Contents

Abstract

The JRC PESETA IV study shows that ecosystems, people and economies in the EU will face major impacts from climate change if we do not urgently mitigate greenhouse gas emissions or adapt to climate change. The burden of climate change shows a clear north-south divide, with southern regions in Europe much more impacted, through the effects of extreme heat, water scarcity, drought, forest fires and agriculture losses. Limiting global warming to well below 2°C would considerably reduce climate change impacts in Europe. Adaptation to climate change would further minimize unavoidable impacts in a cost-effective manner, with considerable co-benefits from nature-based solutions.

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Executive summary

Policy context and purpose

Climate change is one of the biggest threats for humanity, seriously affecting people and nature. With the Green Deal for Europe the EU strives for keeping our planet healthy and aspires to become the first carbon-neutral continent in the world by 2050. Despite this ambition and the target of the Paris Agreement on Climate Change[1] to keep global warming well below 2°C compared to pre-industrial temperatures, greenhouse gas (GHG) emissions worldwide are still growing. Global temperature is now around 1°C higher compared to the preindustrial era and if adequate mitigation strategies are not introduced, global warming could reach 3°C or more by the end of this century.

The primary purpose of the PESETA IV study is to better understand the implications of climate change for the EU. Looking at a range of impact categories this report communicates what sectors and regions of the EU could be most affected and how mitigation and adaptation options can avoid the adverse effects of climate change.

Scenario design

PESETA IV evaluates the benefits (avoided negative impacts) of reducing GHG emissions and the potential of adaptation measures at EU sectoral level. For this, it quantitatively assesses sectoral climate change impacts (damages) in the future when mitigation and adaptation policy actions take place compared to a situation where no policy actions are undertaken. For the scenario without climate policy actions, impacts are assessed at global warming of 3°C and no adaptation. The mitigation benefits of achieving the Paris warming targets are evaluated by estimating impacts with 1.5°C and 2°C global warming.

The evaluation of socioeconomic impacts is made within a specific setting of the state of the economy. That can be static (the economy as of today) or dynamic (the economy of the future). Results of the static approach show how global warming and climate change would impact today's population and economy. This allows to single out the effect of climate change and avoids to make assumptions of demographic and economic developments over long time spans, which are highly uncertain. In the dynamic approach, the economy of the future is based on ECFIN Ageing Report projections of population and economy. Most of the analyses follow the static and dynamic approach, while the assessment of the overall effect on the economy is based on a static general equilibrium model for today's economy.

For some key impacts of global warming, like coastal flooding due to rising sea levels, the costs and benefits of adaptation options are explicitly modelled. For other sectors this is currently not feasible at pan-European scale and adaptation options are considered by reviewing the available literature.

Impact categories

PESETA IV assesses the consequences of climate change for eleven climate impact categories: human mortality from heat and cold waves, windstorms, water resources, droughts, river flooding, coastal flooding, wildfires, habitat loss, forest ecosystems, agriculture and energy supply. The project uses a combination of process-based, empirical, and multi-commodity market models that translate high-resolution projections of climate conditions corresponding to different global warming levels into biophysical and economic impacts.

Interpretation of the results

The study includes as many climate change impacts as feasible at present, but is not comprehensive in terms of the broad range of potential consequences of climate change. Key impacts not studied include those related to aquatic and marine ecosystems, water- and vector-borne diseases, air quality, displacement of people, conflicts and security, the irreversible damage to nature and species losses, and the potentially daunting consequences of passing climate tipping points. The effects of extreme events are also not fully captured in all covered sectors, such as those of heat stress on crop yields and droughts on energy production.

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[1] Adoption of the Paris Agreement FCCC/CP/2015/L.9 (UNFCC, 2015).

This implies that the biophysical and economic impacts quantified in PESETA IV serve as a lower bound of the potential impacts of climate change in the EU. This study should therefore not be interpreted as a complete assessment of the benefits of climate mitigation and adaptation actions in the EU, which could be larger than those presented in this report.

Extensive review reports on the potential impacts of climate change, like the IPCC Assessment Reports, cover a wider range of impacts based on numerous studies. The added value of PESETA IV is that it uses a consistent set of socioeconomic and climate scenarios that allows comparisons of impacts across sectors and regions of the EU to be made.

Estimates reported in this report are inherently uncertain due to uncertainties in climate and socioeconomic projections, the biophysical and economic models implemented and the data used to conceptualise and validate them. Estimates presented herein should thus not be interpreted as forecasts or definitive predictions of future impacts for a particular place, region or country. Rather, they aim to provide insights regarding the general patterns of climate change impacts across the EU and the potential benefits of climate policy actions.

Key findings

Ecosystems, people and economies in the EU are projected to face major impacts from unmitigated climate change

Without climate mitigation (warming of 3°C or more above pre-industrial temperature) and adaptation actions the EU could face the following impacts:

- The alpine tundra domain would contract by 84% and practically disappear in the Pyrenees. The natural climatic tree line would shift vertically up by up to 8 m/year.
- Ecological domains would shift northwards, resulting in severe changes of the prevailing domains in southern Europe and Boreal areas and the encroachment of the Tropical domain in Europe.
- Wildfire and pest outbreaks would become more frequent and severe, increasing biomass loss and carbon release.
- An additional 15 million Europeans living in the proximity of wildland would be exposed to high-to-extreme fire danger for at least 10 days/year.
- Each year nearly 300 million citizens in the EU and UK would be exposed to deadly heatwaves, resulting in a 30-fold rise in deaths from extreme heat (90,000 annual deaths compared to around 3,000 each year today).
- Water resources availability would drop by up to 40% in southern regions of Europe and droughts would happen more frequent in most of southern and western Europe.
- Water scarcity and drought would increasingly affect agriculture, energy production and water supply in regions that already suffer from water stress.
- In the absence of international market adjustments, crop yields would drop by more than 10% in southern Europe.
- Total drought losses for the EU and UK would increase to nearly 45 €billion/year with 3°C warming in 2100 compared to 9 €billion/year at present.
- Almost half a million people in the EU and UK would be exposed to river flooding each year, or nearly three times the number at present, and river flood losses would rise 6-fold in magnitude, reaching nearly 50 €billion/year with 3°C in 2100.
- Coastal flood losses in the EU and UK would grow by two orders of magnitude and climb to 250 €billion/year in 2100, while 2.2 million people would be exposed per year to coastal inundation compared to 100,000 at present.
- If 3°C global warming would occur in today's economy, annual welfare loss in the EU and UK could represent 1.4% of GDP, when considering a limited set of climate impacts (river flooding, coastal flooding, agriculture, droughts, energy supply, mortality from temperature extremes, and windstorms). With 4°C global warming annual welfare loss would be 1.9% of GDP (PESETA III).

The burden of climate change shows a clear north-south divide, with southern regions in Europe impacted more

The south of Europe is expected to suffer relatively more than other parts of Europe with increasing levels of global warming, in large because of consequent changes in high-end temperatures and the spatial and temporal availability of water.

- The frequency of heatwaves rises more dramatically in the south of Europe. With unmitigated climate change, human exposure to severe heatwaves would be multiplied around 30 times at higher latitudes, while it could be 40 to 50 times more in countries in southern Europe (e.g., Spain and Greece).
- During summer, water availability would nearly drop to half in southern European regions that already face the highest water stress. Water resources in northern Europe would increase.
- Electricity production by hydropower would increase in the north, while hydro and nuclear power would reduce in southern Europe due to lower water availability for direct production and river cooling.
- Without market adjustments, wheat and maize yield would drop by more than 10% on average in southern Europe. In northern Europe wheat (maize) yield would increase (decrease) by around 5%.
- With high warming nearly half of total EU and UK drought losses would occur in Mediterranean EU countries, compared to 40% at present.
- In southern mountain ranges the rate of upward tree line shift is double than that at high latitudes, and the alpine tundra would almost completely vanish with high warming.
- The rise in fire danger and exposure to it of people near wildland is stronger at lower latitudes.
- Welfare losses from the climate impacts monetised in PESETA IV show a clear north-south divide, with welfare losses in southern regions that would be several times larger compared to those in the north of Europe.

Climate mitigation can considerably lower the impacts of climate change in the EU

All climate impacts considered in PESETA IV would be reduced significantly with mitigation polices attaining the Paris Agreement targets:

- More than half of the alpine tundra would remain stable, compared to only 16% without mitigation. Vertical tree lines shifts would be reduced by more than 50%.
- The intensity of change in the prevailing ecological domains in southern Europe and Boreal areas and the encroachment of the Tropical domain in Europe would be limited.
- The increase in the number of people near wildland that are annually exposed to at least 10 days of high-to-extreme fire danger would be limited to 5 million, compared to 15 million with 3°C global warming.
- The number of people annually exposed to deadly heatwaves would be reduced by 200 million with 60,000 fewer deaths per year.
- The drop in water resources availability in southern regions would be halved. The number of people living in areas with severe water stress would remain stable, compared to a fourfold multiplication with high warming.
- Annual drought losses would be reduced by 20 €billion/year.
- Each year around 230,000 fewer people would be exposed to river flooding and river flood damage would be halved to 24 €billion/year with 1.5°C in 2100, compared to a 3°C scenario.
- Coastal flood losses would be lowered by more than 100 €billion/year in 2100.
- Welfare losses could be reduced by 75% compared to unmitigated climate change.

Climate change adaptation can reduce unavoidable impacts of climate change in the EU in a cost-efficient way

Even if global warming were limited to well below 2ºC there will be unavoidable impacts in the EU. PESETA IV exemplifies, through pan-European assessments of the costs and benefits of risk reduction measures for river and coastal flooding, that adaptation can reduce climate change impacts in a cost-efficient way.

The analyses show that the benefits of adaption measures are long lasting and avoided climate change damage grows in time and with increasing global warming. In case of unmitigated climate change,

- reducing flood peaks by installing retention reservoirs would reduce annual river flood damage at the end of the century by nearly 40 €billion and around 400,000 fewer people would be exposed each year to flooding in the EU and the UK. The annual investment from now until 2100 to install and maintain the reservoirs would be 3.3 €billion/year. There are additional benefits of nature-based storage areas, such as restoring the natural functioning of floodplain areas and improving ecosystem quality.
- strengthening protection along coastlines of populated and economically pivotal coastal areas would avoid 220 €billion of coastal flood losses each year in the EU and UK at the end of this century, for an annual cost of less than 2 €billion/year from now until 2100. Also 1.4 million fewer people would be exposed each year to coastal flooding. The effects of global warming on sea level rise will continue long after stabilising the climate, hence so will the benefits of coastal adaptation. An unavoidable drawback of the strong rise in sea levels and consequent need for adaptation is that in about 25% of the coastline of the EU the sea would be disconnected from the hinterland by natural or physical barriers, which in some regions can be up to two metres high.

Main findings for different impact categories

Human mortality from heat and cold waves

Global warming will result in a strong net increase in exposure to and fatalities from temperature extremes, assuming there is no adaptation. Regarding heatwaves, with 1.5°C around 100 million Europeans would be exposed each year to an intense heatwave (corresponding to a present 50-year or more extreme heatwave event), or tenfold compared to now. This further grows to 170 million/year with 2°C and nearly 300 million/year, or more than half of the EU and UK population, with 3°C global warming. The rise in exposure to extreme heat is most severe in southern Europe.

Assuming present vulnerability and no additional adaptation, annual fatalities from extreme heat could rise from 2,700 deaths/year now to approximately 30,000 and 50,000 by 2050 with 1.5°C and 2°C global warming, respectively. With 3°C in 2100, each year 90,000 Europeans could die from extreme heat. The rise in fatalities from extreme heat is more acute in southern European countries, with the highest number of fatalities occurring in France, Italy and Spain.

With respect to cold waves, milder winters will reduce significantly exposure to and fatalities from extreme cold, which are already a fraction of the deaths from extreme heat.

These projections do not account for the fact that the European population is ageing. The number of people above 65 years in the EU and UK will grow from 100 million now to 150 million by 2050, which could negatively affect human mortality from temperature extremes. Further, increasing urbanisation could amplify the urban heat island effect, which causes urban and metropolitan areas to be significantly warmer than their surrounding rural areas.

Windstorms

Windstorms are amongst the most damaging natural hazards in Europe, with approximately 5 €billion of estimated annual losses in the EU and UK. Climate model projections suggest that windstorms will not become more intense or happen more frequently with global warming over most of the European land.

With 3°C warming, maximum wind speeds will likely reduce over 16% of the land area, increase over nearly 10% and remain relatively stable over the rest of Europe. Southern Europe is the region with the largest share of the area with an increase in wind extremes (17%), while central-western Europe has the largest share of land for which less intense wind extremes are projected (24%). Furthermore, the number of windy or stormy days does not show significant changes, while there is a robust tendency projected towards more calm days over most of Europe.

Current models project that windstorm losses will not grow due to climate change. Future economic damage from windstorms will increase due to the size of the economy and consequent higher values of the exposed assets and construction costs. Windstorm annual losses are projected to grow to nearly 7 €billion/year in 2050 and to 11 €billion/year by the end of this century.

Water resources

Global warming will result in a general wetting of the north of Europe and a drying of the south. This results in increasing water availability in the north and a reduction in the south. The duration and intensity of water scarcity will grow in already existing water scarce areas in southern Europe. At higher levels of warming, water availability, especially in summer, will also drop in western parts of Europe and at higher latitudes. As a result, new areas that face periods of water scarcity will emerge in countries like Bulgaria, Romania France, Belgium, the Netherlands, Germany, Denmark, and the UK.

The number of people who are living in areas that are considered to be water scarce for at least one month every year could rise from 52 million nowadays to 65 million in a 3°C warming scenario, which is equivalent to 15% of the current EU and UK population. The number of people living in severe water stress, now around 3.3 million, would become fourfold with unmitigated climate. In parts of southern Europe, during summer months practically all available water will be used, and the majority of people and economic activities in these regions would face water scarcity.

Droughts

With global warming, droughts will happen more frequently, last longer and become more intense in southern and western regions of Europe, while drought conditions will become less extreme in northern and northeastern parts of Europe. The Mediterranean region is projected to have the largest relative area affected by an increase in drought with global warming: the frequency of droughts increases across two-thirds of the region in a 1.5°C warming scenario. This rises to more than 80% of the region with 3°C warming, with 23% of the region experiencing a doubling in the frequency of droughts compared to nowadays. Also across 15% of the Atlantic region droughts will happen twice as often with unmitigated climate change.

With 3°C global warming in 2100 total losses from drought in Europe would grow from 9 €billion/year now to 45 €billion/year. Under the mitigation scenarios the rise in damage in 2100 would be approximately halved compared to no mitigation. The Mediterranean and Atlantic regions see the largest rise in drought losses from global warming. Their share in the total EU and UK drought losses progressively increases with warming and would grow to 86% with 3°C warming. Part of the projected rise in future economic losses from droughts is due to the growth of the economy. Yet, changes in the economy also dampen future losses when compared to the size of the economy because drought-sensitive sectors, and especially agriculture, are projected to become less economically prevalent in future EU economies.

River floods

Global warming and continued development in flood prone areas will progressively increase river flood risk. With 3°C global warming by the end of the century, river flood damage in the EU and UK would be six times present losses of 7.8 €billion/year and nearly half a million people would be exposed to river flooding each year, compared to 170,000 now. Keeping global warming with 1.5°C would halve these economic impacts and reduce the number of people exposed by 230,000.

Adequate adaptation strategies can further substantially reduce future flood impacts. Four adaptation options have been explored at pan-European scale: reducing flood peaks using retention areas, strengthening existing dyke systems, implementing building-based damage reduction measures, and relocation.

Reducing flood peaks using retention areas shows the strongest potential to lower direct impacts in a cost-efficient way. Implementing the optimal design for the 3°C warming scenario would require for the EU and UK an average annual investment of 3.3 €billion/year over the period 2020-2100 (undiscounted values), which would lower economic damage from flooding by 40 €billion/year (82% reduction) at the end of the century. Additional benefits include the restoration of the natural functioning of floodplain areas and hereby improving ecosystem quality. Strengthening existing dyke systems can also prevent floods from happening (reducing the expected damage with 68% for the 3°C warming), yet they can transfer risk downstream and stimulate further development behind the flood barriers. Implementing building-based damage reduction measures do not avoid floods, but they can reduce EU expected damage by 50% for the 3°C warming scenario, and this in a very cost-efficient manner because they require limited implementation investments. Relocation is less cost-efficient and subject to large variability in the implementation costs, and has lower social acceptance.

Coastal floods

Extreme sea levels in Europe could rise by as much as one metre or more by the end of this century due to global warming. Consequent damage from coastal flooding will rise sharply for all EU countries with a coastline if current levels of coastal protection are not raised. Without mitigation, annual economic damage in the EU and UK would grow to 239 €billion by 2100 and the population exposed to coastal flooding would reach 2.2 million. With moderate mitigation the damage would be reduced by half (to €111 billion/year) and the exposed population would be 1.4 million/year, still significantly greater than at present (1.4 €billion/year of damage and 0.1 million people annually population).

The potential of raising dykes to reduce coastal impacts has been assessed as an adaptation option, likely an unavoidable strategy along developed stretches of Europe's coastlines given the pronounced projected rises in sea level extremes. Raising dykes would reduce damage and the population affected by around 90% and 60% in 2100, respectively. The average annual cost of adaptation over the period 2020-2100 would be less than 2 €billion/year for the EU and UK, which is about two orders lower than the avoided coastal flood losses by the end of the century. This means that investing now in coastal protection will have very large (and growing) benefits in the long term.

The protected areas would be the urbanised and economically important areas, and cover about one fifth of the European coastline. The average raise in protection over these stretches is around one metre, but in some places more than two metres. This implies that along many densely populated and economically pivotal coastal stretches of the EU the shoreline may become disconnected from hinterland areas.

Wildfires

The probability of high-to-extreme wildfire danger is projected to rise nearly everywhere in Europe as a result of changing weather conditions associated with global warming. The projected increase in fire danger intensity and number of days with high-fire potential amplifies with the level of warming, and is strongest in southern European countries, where fires already occur more often and are more intense. Yet, recent events in Sweden, Ireland and the UK show that fires are not limited to southern Europe.

The number of people in Europe that live near wildland and that are exposed to high-to-extreme levels of fire danger for at least 10 days per year would grow by 15 million (+24%) with 3°C global warming, compared to now. When limiting global warming to 1.5°C, this would be 10 million fewer people.

Climate change would also result in major shifts northwards of ecological domains. Especially southern Europe and Boreal areas would experience severe changes in the prevailing ecological domain components. Higher levels of warming also increase the likelihood that the Tropical domain would encroach in Europe. The profound transformation of bioclimatic conditions will outpace the time required for vegetation to adapt to it and pose a main stress on the structure and composition of wildland vegetation (forests, shrub and grassland). This will increase the vulnerability to fires, but also affect vegetation recovery after the fire.

Stringent mitigation would limit the contractions and expansions. Yet, mitigation alone is not enough to avoid adverse climate change impacts and adaptation strategies will be needed in order to enhance social–ecological resilience to wildfires.

Alpine tundra habitat loss

The alpine tundra domain occurs at the top of high mountains in Europe and about 98% of its domain is in the Pyrenees, Alps and Scandes. The domain is rich in biodiversity and provides key ecosystem services. Due to the tight ecological-climatic bands in mountains, climate change could have major effects on alpine ecosystems. In a 3°C warming scenario, the alpine tundra domain over Europe would shrink by 84% of its present size, including the loss of precious Natura 2000 sites. In the Pyrenees high warming could lead to a near disappearance of the alpine tundra, while in the Alps and Scandes it would shrink by around 75% and 87% respectively of its present size. Limiting warming to 1.5°C would restrict alpine tundra contraction to 48%, most strongly in the Alps where the domain contraction would be limited to a loss of 36%.

The natural climatic treeline is projected to move vertically upwards by up to 8 metres every year with unmitigated climate change. The rate of treeline shift is generally faster at lower latitudes, where climatic treelines are already higher. In the southernmost mountain regions the treeline moves upwards by around 6-7 m every year in the 1.5°C warming scenario, compared to 2-3 m/year at high latitudes. In a 3°C warming scenario, the treeline in the Pyrenees could rise by 642 m, in the Alps by 526 m and in the Scandes by 336 m.

The projected changes have implications for vital ecosystem services, habitat for biodiversity, and recreational services such as skiing. Adaptation is challenging because of the unique topographic, soil and climatic characteristics of high mountain systems.

Forest ecosystems

In recent years, about 14 billion tonnes of forest biomass in the EU and UK, or two third of the total biomass, was found to be potentially vulnerable to natural disturbances. Nearly half of that amount (46%) is threatened by windstorms, followed by forest fires (29%) and insect outbreaks (25%). Hotspot regions with high forest susceptibility to windstorms, fires and insect outbreaks are located in both southern and northern Europe. This spatial pattern is strongly controlled by the interplay of forest characteristics with the background climate.

Over the last two decades, an increasing amount of forests in Europe has become vulnerable to insect outbreaks, particularly in high-latitude regions. The combination of rising temperature and changes in precipitation in the last two decades has likely reduced plant defence mechanisms and increased their vulnerability to insect outbreaks. No clear trends can be detected in the forest vulnerability to windstorms and fires over this period.

Global warming is likely to increase natural disturbances in the future, especially those from fires and insect outbreaks that are more sensitive to climate. As a result, key forest ecosystem services - such as carbon sequestration, erosion control, water regulation or wood supply - could be seriously affected in the near future.

Agriculture

Climate change is expected to lower grain maize potential yield by -11% and -5% on average in southern and northern Europe respectively under a 2°C warming scenario. In the absence of irrigation, declines in yield of over 20% are projected for all EU countries, with crop losses up to 80% in some southern European countries (Portugal, Bulgaria, Greece and Spain). This implies that grain maize production may no longer be viable in areas where irrigation is restricted due to water scarcity and precipitation significantly decreases. Even adaptation strategies, such as changing sowing dates and the sown variety, would not suffice to offset the projected strong reduction in rain-fed grain maize yield.

The production of wheat, which is mostly a rain-fed crop in Europe, would increase by 5% on average in northern Europe because of changing precipitation regimes, an anticipated growing cycle and enhanced CO_2 fertilization. In southern regions of Europe, however, yield reductions of 12% are estimated (in some areas yields could be halved) due to the strong decrease in precipitation. However, changing varieties could have a large beneficial effect for rain-fed wheat production.

The negative effects of climate change on crop yields in Europe projected by biophysical models may considerably be reduced by changes induced by market adjustments, given the severe climate change impacts on large agricultural producers outside Europe. Therefore, EU production could slightly increase because Europe is projected to have a comparative advantage versus other world production regions with larger negative effects in terms of climate change impacts on agricultural productivity.

Energy production

The effects of climate change on different power sources vary throughout Europe and depends on the future energy mix. In northern Europe, where there is already high capacity for hydropower, the increase in water resources availability with global warming could lead to more hydropower production. Since hydropower has a lower marginal cost compared to thermal sources, the demand for power from thermal sources like biomass, coal, gas and oil would reduce in these regions. Depending on the local electricity production mix, the substitution effect is different, e.g. mainly biomass in Sweden, coal in Finland, oil in Lithuania and gas in Latvia. This would lead to economic benefits in northern Europe of around 1.3 €billion/year (2015 values) with 3°C warming.

In southern regions water resources are expected to become scarcer with increasing levels of global warming. This would result in a reduction in hydropower and nuclear production. The substitution by non-nuclear thermal plants that have higher marginal production costs could lead to an increase in production costs by around 0.9 €billion/year (2015 values) with 3°C warming.

The direct impacts of climate change on wind and solar production are not significant. However, in the 2050 power system that is in line with a 2°C mitigation scenario wind and solar capacity would increase in southern regions to compensate for the lost hydropower and nuclear power production.

Economic integration

Seven climate impact categories have been assessed in broader economic terms, assuming that future climate would happen today (comparative static setting assuming today's economic structure and size): river floods, coastal floods, agriculture, energy supply, droughts, windstorms and human mortality. The economic assessment does not evaluate the full economic impacts of climate change because of the limited coverage of climate impacts.

Exposing present economy to global warming of 3°C would result in an annual welfare loss of 175 €billion (1.38% of GDP). Under a 2°C scenario the welfare loss would be 83 €billion/year (0.65% of GDP), while restricting warming to 1.5°C would reduce welfare loss to 42 €billion/year (0.33% of GDP). PESETA III estimated a welfare loss of 1.9% of GDP for a 4°C warming scenario, indicating that economic impacts further grow with the intensity of global warming.

Human mortality from extreme heat dominates the economic climate impacts, but its contribution is strongly dependent on the monetary valuation of human life. The magnitude of welfare losses in southern regions of Europe is estimated to be several times larger compared to that in the north. Welfare losses related to the impact categories considered would be substantially reduced when reaching the Paris Agreement global warming targets. In particular, limiting warming to 2°C would halve economic impacts compared to a 3°C scenario, while achieving the stringent Paris target of 1.5°C would lower welfare loss by 75%.

1 Introduction

Climate change is among the biggest threats for humanity, seriously affecting human health[1], the natural environment[2], and security[3]. Despite the ambition of the Paris Agreement[4] on Climate Change to keep global warming ‘well below 2°C’ compared to pre-industrial temperatures and to pursue a more ambitious goal of 1.5°C, greenhouse gas emissions worldwide are still growing. As global temperature is now around 1 °C higher compared to the late 19th century, the likelihood that global warming will surpass the Paris targets is growing. If adequate mitigation strategies are not introduced global warming could reach 3°C or more by 2100.

The EU is preparing to minimise future impacts of unavoidable climate change in its member states through the EU Adaptation Strategy. A key objective of the strategy is to promote better informed decision-making by refining knowledge gaps (identifying and addressing them) and enhance knowledge sharing and transfer across Europe. Action 4 of the Strategy, in particular, aims to bridge the knowledge gap for some key unknowns. These include 'information on damage from climate change’ and the ‘benefits and costs of adaptation'. Climate impacts in Europe are not yet fully understood and quantified, especially with regard to extremes or impacts on ecosystems and security. Moreover, there is a clear need for a better understanding of how climate impacts could be reduced with sectoral adaptation measures and at what economic cost. Many of these issues remain challenging research topics, especially the quantification of the vulnerability of people, economic sectors and ecosystems to climate change and the economic analysis of adaptation.

The series of PESETA (Projection of Economic impacts of climate change in Sectors of the European Union based on bottom-up Analysis) projects of the Joint Research Centre (JRC) of the European Commission aim to reduce the knowledge gap on climate change impacts and adaptation. Together, they represent a continuous effort to integrate cumulated and new JRC research to better understand some of the key potential consequences of future climate change in the EU, both in biophysical and economic terms, and the costs and benefits of adaptation. This is relevant for the ongoing development and implementation of European climate policy on mitigation and adaptation.

This report summarises the main outcomes of the JRC PESETA IV project. The project integrates a common set of climate scenarios and socioeconomic data with detailed biophysical process simulation and economic modelling. Impacts are estimated for the warming targets set out in the Paris Agreement (1.5°C and 2°C) as well as a higher level of warming (3°C), which is closer to what could be expected by the end of the twenty-first century without adequate mitigation. The assessment looks at effects on people, economic sectors and the environment based on bottom-up impact analyses for agriculture, energy, river flooding, coastal floods, drought, habitat loss, forest fires, water, human impacts of heat and cold waves, forest ecosystems, and windstorms.

The JRC PESETA IV project improves and widens the overall assessment along its three main dimensions, compared to JRC PESETA III. Firstly, a larger ensemble of climate scenarios is used to better account for uncertainties in both greenhouse gas emissions and in the climate models that translate these emissions into climate projections. Secondly, new impact categories are included in the impact modelling: mortality from extreme heat and cold, economic losses and fatalities from windstorms, economic losses from drought and impacts on forest ecosystems. Thirdly, the river and coastal flood analyses explicitly model adaptation following a cost-benefit approach, while agriculture also considers adaptation to some extent. For the other impact areas possible adaptation options are discussed.

The study includes as many climate change impacts as feasible at present, but is not comprehensive in terms of the broad range of potential consequences of climate change. The project performed assessments of impacts for several climate extremes (heat and cold waves, drought, windstorms, river and coastal flooding), yet some sector impact analysis not do fully capture the consequences of changes in such extremes. Hence, the biophysical and economic impacts quantified serve as a lower bound of the potential impacts of climate change in the EU. Estimates reported here are inherently uncertain and should not be interpreted as forecasts or definitive predictions of future impacts for a particular place, region or country. Rather, they aim to provide insights regarding the general patterns of climate change impacts across the EU and the potential benefits of climate policy actions.

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[1] https://www.who.int/globalchange/global-campaign/cop21/en/

[2] https://www.ipbes.net/global-assessment-report-biodiversity-ecosystem-services

[3] https://www.pewresearch.org/global/2019/02/10/climate-change-still-seen-as-the-top-global-threat-but-cyberattacks-a-rising-concern/

[4] Adoption of the Paris Agreement FCCC/CP/2015/L.9 (UNFCC, 2015)

The audience of this report is the policymakers' community, therefore it is intended to be concise with a non-technical language. The report does not enter into the technical aspects of the climate impact and adaptation assessment, which can be found in the related JRC technical reports listed below.

Barredo J I, Mauri A and Caudullo G (2020). *Impacts of climate change in European mountains - Alpine tundra habitat loss and treeline shifts under future global warming*, EUR 30084 EN, Publications Office of the European Union, Luxembourg, ISBN 978-92-76-10717-0, doi: 10.2760/653658, JRC115186.

Bisselink B, Bernhard J, Gelati E, Adamovic M, Guenther S, Mentaschi L, Feyen L and de Roo A (2020). *Climate change and Europe's water resources*, EUR 29951 EN, Publications Office of the European Union, Luxembourg, ISBN 978-92-76-10398-1, doi: 10.2760/15553, JRC118586.

Cammalleri C, Naumann G, Mentaschi L, Formetta G, Forzieri G, Gosling S, Bisselink B, De Roo A and Feyen L (2020). *Global warming and drought impacts in the EU*, EUR 29956 EN, Publications Office of the European Union, Luxembourg, ISBN 978-92-76-12947-9, doi:10.2760/597045, JRC118585.

Costa H, de Rigo D, Libertà G, Houston Durrant T and San-Miguel-Ayanz J (2020). *European wildfire danger and vulnerability in a changing climate: towards integrating risk dimensions*, EUR 30116 EN, Publications Office of the European Union, Luxembourg, ISBN: 978-92-76-16898-0, doi:10.2760/46951, JRC119980.

Després J and Adamovic M (2020). *Seasonal impacts of climate change on electricity production*. EUR 29980 EN, Publications Office of the European Union, Luxembourg, ISBN 978-92-76-13095-6, doi:10.2760/879978, JRC118155.

Dosio A (2020). *Mean and extreme climate in Europe under 1.5, 2, and 3°C global warming*, EUR 30194 EN, Publications Office of the European Union, Luxembourg, ISBN 978-92-76-18430-0, doi:10.2760/826427, JRC120574.

Dottori F, Mentaschi L, Bianchi A, Alfieri L and Feyen L (2020). *Adapting to rising river flood risk in the EU under climate change*, EUR 29955 EN, Publications Office of the European Union, Luxembourg, ISBN 978-92-76-12946-2, doi: 10.2760/14505, JRC118425.

Forzieri G, Girardello M, Ceccherini G, Mauri A, Spinoni J, Beck P, Feyen L and Cescatti A (2020). *Vulnerability of European forests to natural disturbances*, EUR 29992 EN, Publications Office of the European Union, Luxembourg, ISBN 978-92-76-13884-6, doi: 10.2760/736558, JRC118512.

Hristov J, Toreti A, Pérez Domínguez I, Dentener F, Fellmann T, Elleby C, Ceglar A, Fumagalli D, Niemeyer S, Cerrani I, Panarello L and Bratu M (2020). *Analysis of climate change impacts on EU agriculture by 2050*, EUR 30078 EN, Publications Office of the European Union, Luxembourg, ISBN 978-92-76-10617-3, doi: 10.2760/121115, JRC119632.

Naumann G, Russo S, Formetta G, Ibarreta D, Forzieri G, Girardello M and Feyen L (2020). *Global warming and human impacts of heat and cold extremes in the EU*, EUR 29959 EN, Publications Office of the European Union, Luxembourg, ISBN 978-92-76-12954-7, doi:10.2760/47878, JRC118540.

Spinoni J, Formetta G, Mentaschi L, Forzieri G and Feyen L (2020). *Global warming and windstorm impacts in the EU*, EUR 29960 EN, Publications Office of the European Union, Luxembourg, ISBN 978-92-76-12955-4, doi:10.2760/039014. JRC118595.

Szewczyk, W., Feyen. L., Matei, A., Ciscar, J.C., Mulholland, E., Soria, A. (2020). *Economic analysis of selected climate impacts*, EUR 30199 EN, Publications Office of the European Union, Luxembourg, ISBN 978-92-76-18459-1, doi: 10.2760/845605, JRC120452.

Vousdoukas M, Mentaschi L, Mongelli I, Ciscar JC, Hinkel J, Ward P, Gosling S and Feyen L (2020). *Adapting to rising coastal flood risk in the EU under climate change*, EUR 29969 EN, Publications Office of the European Union, Luxembourg, ISBN 978-92-76-12990-5, doi:10.2760/456870, JRC118512.

2 Methodology

2.1 Project implementation

Figure 1 gives an overview of the project, which involves three main stages. In the first stage, a common set of climate change and socioeconomic data are prepared to feed the biophysical and economic impact modelling. In the second stage, separate biophysical models are run in order to quantify how the projected changes in climate variables affects agricultural crop yields, energy supply, river floods, coastal floods, heat and cold waves, drought, habitat suitability, forest fires, forest ecosystems, water resources and windstorms. In stage three, a subset of the biophysical impacts are analysed in terms of direct human impacts and economic losses; in particular, for agriculture, energy supply, river floods, coastal floods, heat and cold waves, drought and windstorms. Finally, the direct human and economic impacts are integrated into an overall economic model in order to estimate corresponding welfare losses.

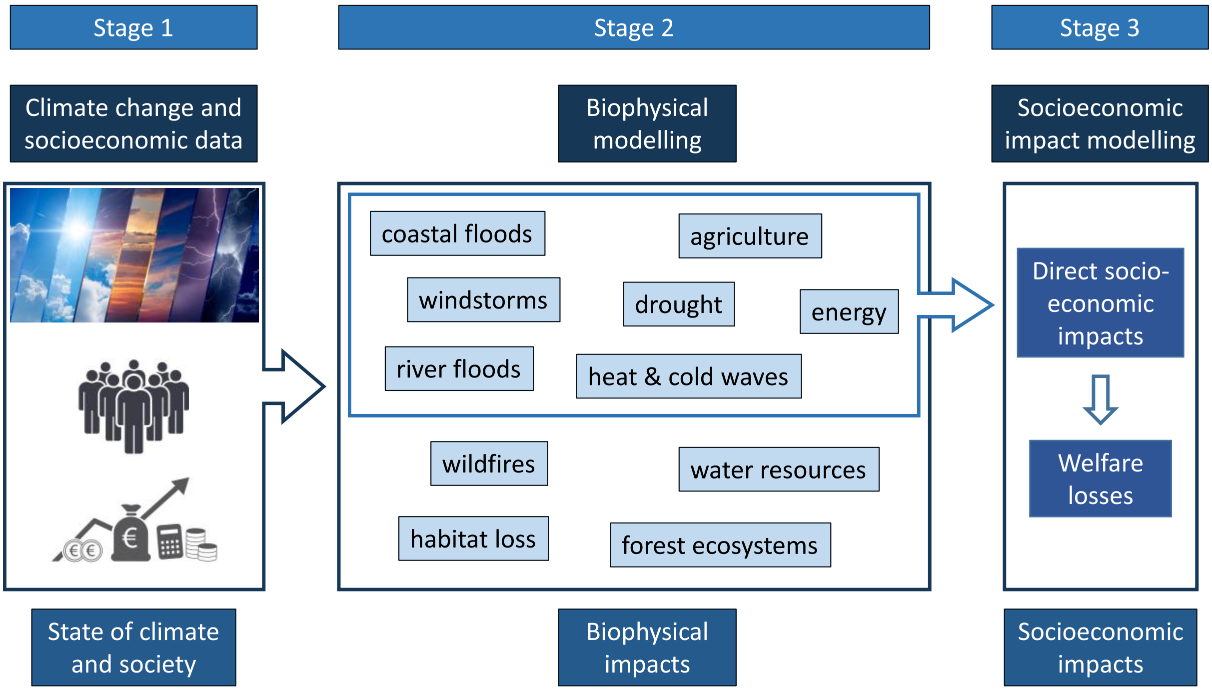

Figure 1. Overview of the project methodology

2.2 Scenario design

The level of global warming depends on the concentration of greenhouse gasses (GHG) in the atmosphere. Future emissions are determined by human activities and socioeconomic development. In order to account for uncertainty in future emissions a range of plausible pathways of GHG concentrations are considered in the scientific community to visualise alternative futures. These Representative Concentration Pathways (RCPs) describe different levels of greenhouse gas concentrations and radiative forcing that might occur in the future (Van Vuuren et al., 2011).

The project evaluates the effects of GHG mitigation by estimating climate impacts for the Paris targets (1.5°C and 2°C) and a higher warming level (3°C). It considers a common set of climate projections under a moderate mitigation (RCP4.5) and high emissions (RCP8.5) pathway in order to evaluate impacts both for low and high levels of global warming.

The project assesses socioeconomic impacts of global warming within a specific setting of the state of the economy. That can be the economy as of today (static approach) or the economy of the future (dynamic approach). The static approach portrays how global warming and climate change would impact today's population and economy. This approach is appropriate in order to avoid making assumptions on the future (long-term) evolution of the socioeconomic systems (demography, economy size, sectoral decomposition of the GDP, etc.), which are highly uncertain and could greatly distort the sectoral impacts of climate change. An additional advantage of this methodology is that it aids the comparison of the severity of the different impacts against the same economic system metrics. However, the absolute damage figures may be unrealistic (and highly conservative), as they do not consider the long-term dynamic growth of the overall economies.

The dynamic socioeconomic assessment evaluates how climate at the different global warming levels would impact EU society as projected for 2050 and 2100 according the ECFIN Ageing Report projections of population and economy (European Commission, 2014; Havik et al., 2014). As a 3°C warming scenario is unlikely to occur by mid-century, only the Paris targets are considered in 2050, while in 2100 the three warming levels are considered. Comparison of the static and dynamic economic analyses allows the effects of climate and socioeconomic changes on future climate risk to be disentangled. The dynamic assessment has been implemented in all impact assessments that quantify damage in monetary terms, while the assessment of the overall effect on the economy is based on a static general equilibrium model for today's economy.

2.3 Projections of future climate

The climate models used in PESETA simulate physical climate processes on a grid that covers the whole of Europe. The climate models used are known as regional climate models (RCMs), which mean that they produce climate projections at a relatively fine scale. Climate simulations differ between climate models, even when the forces that drive the climate, such as greenhouse gas emissions, are the same, and when all models are built in plausible ways. This is known as climate modelling uncertainty. To account for this uncertainty, the project uses an ensemble of 11 climate models that took part in a large, on-going climate model inter-comparison project called Coordinated Regional-climate Downscaling Experiment over Europe (EURO-CORDEX[1]).

Simulations of the past climate from climate models can differ from the actual measured climate. Climate model simulations are therefore often corrected to account for such biases, through a statistical procedure known as "bias correction". All of the climate model simulations used in PESETA were bias corrected using an established method that has been extensively used in other studies.

The project implements the "time sampling" approach to select climate conditions at the global warming levels under the two transient pathways considered (RCP4.5 and RCP8.5). This assumes that the impacts at a certain warming level can be derived from the transient climate projections by considering climate and corresponding impacts over a 30-year time window centred on the year when the targeted global warming level is reached. It is thus possible to decouple impacts from the time at which a specific global warming level is reached, and to look at how different warming levels affect future societies at different points in time. For most climate variables and impacts the effect of the pathway to reach a global warming level is small over Europe compared to the climate model variability (Maule et al., 2017).

For time-variant changes such as sea level rise, which will continue long after climate has stabilised at a certain global warming level, the time dimension however remains critical. Therefore, results of the coastal impact analysis with a dynamic economic setting are presented for 2050 and 2100 rather than for the global warming levels.

2.4 Socioeconomic projections

The dynamic socioeconomic scenario considered is that of the ECFIN Ageing Report (European Commission, 2014; Havik et al., 2014). The EU Ageing Report projections are based on very detailed analyses of the determinants of long-term growth in Europe, notably demographics, labour market and planned legislation measures and furthermore, they have been assessed by the EU member states economic departments and other related ministries. As the Ageing Report refers to the period to 2060, the projections have been extended to the year 2100 based on plausible assumptions. The rules of factor accumulation regarding total factor productivity (TFP) and capital are the same as those in the Ageing Report (the contribution of TFP and capital for the 2060-2100 period are the same as for the 2055-2060 period). The labour force projections are the

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[1] http://www.cordex.org/

same as those of the overall population growth, which come from the United Nations (UN) medium variant case (UN, 2015).

The project uses the 2015 Ageing Report projections that were available at the time of the project implementation. For the EU as a whole, there are no major differences compared to the more recent 2018 Ageing Report projections: EU GDP growth is slightly lower in the 2018 Aging Report over the period 2025-2050, while it is marginally higher during 2055-2070. For some Member States, however, there are substantial variations, with lower average annual GDP growth rates in the 2018 Ageing Report for Cyprus, Italy, Greece and Portugal (e.g. Italy -1.3 percentage points difference in 2020-2035), and the largest upward variations for Malta, Latvia, Slovakia and Romania (e.g. Malta +1.8 percentage points in 2020-2025).

2.5 Overview of impact models

Table 1 presents an overview of the modelling approaches used in PESETA IV. The project uses a combination of process-based and empirical models. Process-based approaches simulate physical or biological processes that explicitly describe system behaviour in response to climate change. Empirical approaches seek correlative relationships among the data in line with mechanistic understanding, but without necessarily fully describing system behaviour and interactions. Generally, process-based models include some empirical information and the correlative relationships of empirical models assume a link to processes. So in practice many models use a hybrid approach, combining a process-based and empirical representation of relationships (Adams et al., 2013). More details on the models used can be found in the references listed in Table 1 and in the separate reports in which the PESETA impact analyses are described (see reference added to each short description below).

Heat and cold waves

The Heat and Cold Wave Magnitude Index are derived from the bias-corrected climate projections and take into account the duration and intensity of the hot and cold spells. Extreme value analysis is applied to these indices in order to understand how the intensity and frequency of such extremes could change with global warming. Human exposure is appraised by combining modelled heat and cold extremes with high resolution population density maps. Human mortality rates from heat and cold extremes are derived from reported fatalities in disaster records and simulated population exposure. These are then applied to the projections of heat and cold waves, assuming no changes in human vulnerability. More details in Naumann et al. (2020).

Windstorms

Daily maximum wind velocity simulated by the climate models is used as an indicator of windstorms. Extreme value analysis is applied to this index in order to understand how often and with what intensity wind extremes could happen under different levels of global warming. Exposure of the construction stock and population to windstorms is appraised by combining modelled wind extremes with high resolution land use and population density maps. Damage functions and mortality rates are derived from reported economic windstorm losses and fatalities in disaster records and simulated construction stock and population exposure. The damage function and mortality rates are then applied to the projections of windstorms, assuming no changes in vulnerability. Projections of daily wind speed are also used in the analysis on wind energy supply (average wind speed) and forest disturbances (extreme wind speed). More details in Spinoni et al. (2020).

Water resources

A hydrological model is used to simulate the spatial and temporal distribution of water on, above and below the earth surface across Europe. It takes into account spatial variataions in land use, soil properties and vegetation characteristics and uses as input simulated climate variables such as precipitation, temperature, wind, radiation and humidity. The model also includes water extraction by different sectors, including agriculture (irrigation and live stock), energy, public water and industrial water use. Irrigation water demand is estimated dynamically within the model, while the other uses are estimated based on national water statistics. Water scarcity is estimated based on the net water consumption versus available renewable water resources of a region. Exposure of economic activity and population to water shortage is evaluated by intersecting simulated water scarcity with regional statistics on production output of sectors and high resolution population density maps. Projections of river flows by the hydrological model are also used in the analysis on drought (low river flows), floods (high river flows), and energy supply (average river flows for hydropower and cooling of power production). More details in Bisselink et al. (2020).

Table 1. Overview of impact modelling in PESETA IV

Impact category	Biophysical modelling	Socioeconomic impact modelling
Heat and cold waves	Heat and cold wave magnitude index modelling (Russo et al., 2015); extreme value analysis (Mentaschi et al., 2016)	Human exposure and empirical mortality rates (Forzieri et al., 2017)
Windstorms	Windstorm indicator modelling (Outten et al., 2013); extreme value analysis (Mentaschi et al., 2016).	Empirical wind damage function (Spinoni et al., 2019) and human mortality rates (Forzieri et al., 2017)
Water resources	Hydrological and water use modelling with LISFLOOD (Van der Knijff et al., 2010); water scarcity analysis (Bisselink et al., 2018).	Human exposure to water scarcity (Bisselink et al., 2020).
Drought	Hydrological and water use modelling with LISFLOOD; extreme low flow analysis (Forzieri et al., 2014).	Empirical drought loss functions (Cammalleri et al., 2020).
River flooding	Hydrological and water use modelling with LISFLOOD; extreme high flow analysis; flood inundation modelling (Alfieri et al., 2015a).	Empirical water depth-damage functions (Alfieri et al., 2015b).
Coastal flooding	Sea level rise projections; surge, wave and tide modelling, flood inundation modelling (Vousdoukas et al., 2017).	Empirical water depth – damage functions (Vousdoukas et al., 2018).
Wildfires	Numerical simulation weather-driven fire danger using Canadian Fire Weather Index (FWI) system (de Rigo et al., 2017); Estimation of wildland-urban interface (Costa et al., 2020). Modelling shifts in ecological domains (de Rigo et al., 2016).	
Habitat loss	Köppen-Geiger climate classification of alpine tundra (Kottek et al., 2006); mapping of treeline position (Körner and Paulsen, 2004).	
Forest ecosystems	Empirical vulnerability analysis of European forests to fires, windstorms and insect outbreaks (Forzieri et al., 2020)	
Agriculture	Crop yield modelling with World Food Studies Simulation Model (WOFOST) model (Blanco et al., 2017; de Wit et al., 2019).	Agriculture economic modelling with the Common Agricultural Policy Regionalised Impact (CAPRI) model (Britz and Witzke, 2014)
Energy supply	Energy supply modelling with POLES energy model (Després et al., 2018).	Modelling of energy production costs (Després et al., 2018).
Economic integration		Integrated economic modelling with Climate assessment General Equilibrium (CaGE) model (Pycroft et al., 2016; Ciscar et al., 2011).

Drought

The low flow spectrum of the river flow simulations are analysed to estimate streamflow drought, which reflects the spatially integrated negative anomaly in water resources over river basins. Extreme value analysis is applied to annual minimum river flows to project how frequently and with what intensity drought could occur in view of global warming. The vulnerability to drought is quantified based on reported economic losses from drought disaster records and the simulated drought intensity for these events. The impacts are further disaggregated over drought sensitive sectors based on expert and literature information on drought sensitivity of different sectors and statistics on the economic value of these sectors. The derived statistical relationship between drought intensity and damage in drought-sensitive sectors, which in the analysis is assumed to be static, is then applied to the projected drought conditions with warming in order to quantify the corresponding drought risk. More details in Cammalleri et al. (2020).

River flooding

High river flows of the hydrological simulations are used to estimate the probability of occurrence and intensity of river floods. When river water levels exceed current flood protection standards the corresponding inundated areas and flood depth are estimated. This information is then combined with high resolution population and land use maps in order to quantify people and assets exposed to river flooding. With country-specific statistical relations between flood water depth and damage for different land use types the direct economic loss is calculated for each flood event. The analysis then evaluates the cost and benefits of the following adaptation options: strengthening of existing dyke systems, implementing flood damage reduction measures for buildings, building of retention areas to store flood waters, and relocation of people and buildings from flood-prone to flood-safe areas. The evaluation of each adaptation strategy is performed using a cost-benefit analysis that optimises the overall costs of implementation and avoided economic flood damage over the life time of the measure. More details in Dottori et al. (2020).

Coastal flooding

Extreme levels along Europe’s coastlines are estimated based on state-of-the-art projections of sea level rise and the modelling of waves, storm surges and tides using simulated climate variables such as wind speed and pressure. When extreme sea levels overtop present coastal protection the corresponding flood inundation extent and depth are estimated. Similar as for river flooding, this information is then combined with high resolution population and land use maps in order to quantify people and assets exposed to coastal flooding. With country-specific statistical relations between coastal flood water depth and damage for different land use types the direct economic loss is calculated for each flood event. The analysis then evaluates the cost and benefits of increasing coastal protection through dyke improvements along the European coastline, assuming that in densely populated and highly developed coastal communities the preferred option is to ‘hold the line’ of existing dyke systems. The evaluation of the optimal design level is performed using a cost-benefit analysis that optimises the overall costs of implementation and avoided economic flood damage over the life time of the measure. More details in Vousdoukas et al. (2020).

Wildfires

Weather-driven fire danger is estimated numerically on a daily basis. The model combines temperature, wind speed, relative humidity, and precipitation projected by the climate models and also accounts for the cumulative dynamic effects of the weather in the previous days. Daily fire danger is classified considering six classes of fire danger from days with low danger up to days with extreme danger and the probability of occurrence (average number of days in a year) of the different classes of fire danger is calculated. Potential changes in ecological domain and local ecological patterns with global warming, which are an indication of future vegetation vulnerability to fire, is assessed based on the projected changes in temperature. The vulnerable interface between wildland and human presence is assessed at high-resolution by combining land use information and population density maps. More details in Costa et al. (2020).

Habitat loss

Alpine tundra is mapped using a climate classification equivalent to polar climates, where the mean temperature of the warmest month is less than 10°C. The projections of temperature by the climate models is corrected for bias and downscaled to high resolution accounting for altitude effects. Projected changes in the alpine tundra domain are then classified in three potential categories: stable, contraction and expansion. The climatic treeline position is located using a growing season canopy temperature threshold of 7.6°C. Treeline shifts with global warming are assessed in 16 mountain regions in Europe, from the Mediterranean islands to the Boreal areas and from the Iberian Peninsula to the Carpathians, including the more prominent treeline ecotones of Europe. Natura 2000 sites projected to be affected by changes of the alpine tundra are identified by overlaying projected alpine tundra changes with the map of Natura 2000 sites. More details in Barredo et al. (2020).

Forest ecosystems

The vulnerability of European forests to three major natural disturbances is assessed: fires, windstorms and insect outbreaks. For each disturbance type, a multi-variate regression model is derived to predict biomass losses based on a number of forest, climate and landscape parameters. Forest features include vegetation parameters describing the forest state and productivity, such as biomass, growing stock volume, leaf area index, tree age, tree density and tree diameter. Climate information includes long term averages of temperature and precipitation and anomalies therein in the years preceding the disturbance, as well as extremes of wind and aridity in the year of the disturbance. Landscape features include population density, spatial vegetation variability metrics and geomorphological parameters. The vulnerability models are calibrated and validated using a large set of records of forest areas affected by natural disturbances over the period 2000-2017. More details in Forzieri et al. (2020).

Agriculture

A spatially-distributed crop model is used to simulate yield for wheat, grain maize, barley, sunflower, winter rapeseed and sugar beet. The model uses bias-adjusted daily temperature and precipitation together with other meteorological variables (e.g. wind, relative humidity, global radiation) simulated by the climate models. It also accounts for the effects on crop growth of elevated atmospheric CO_2 concentrations. Water limitation effects are evaluated by simulating both potential yield assuming sufficient water for irrigation and rain-fed yield (without irrigation).

A partial equilibrium, large-scale economic, global multi-commodity, agricultural sector model was used to assess EU market adjustments (production, land use, consumption, income, prices and trade) in response to crop yield changes in the EU and in other parts of the world due to global warming. Yield estimates are obtained from an ensemble of global crop models forced by global climate projections, which for the EU partially overlap with the European scale crop yield projections. The global models do not consider water availability constraints, the effect of elevated atmospheric CO_2 concentrations, or changes in crop varieties and sowing dates. More details in Hristov et al. (2020).

Energy supply

The effects of global warming on energy supply in the EU is assessed using a global energy model. It covers the entire energy system, from primary supply (e.g. fossil fuels, renewables) to transformation (power, biofuels, hydrogen) and sectoral demand. The following sources of supply are considered: hydro, solar, wind, nuclear, and other thermal sources (coal, gas, oil and biomass). The energy model is applied at country scale with a yearly time step but accounting for seasonal variability in climate and water availability. Solar and wind production are estimated based on efficiency relations with temperature and wind speed respectively. Hydrological simulations of the water resources analysis are used to assess hydropower potential, and together with water temperatures, also cooling water availability for nuclear and other thermal plants. All power sources are inter-linked, since the representation of the whole energy sector implies a balance between supply, prices and demand. Hence, climate induced changes in the supply of one source can also affect the supply of other energy sources. More details in Després and Adamovic (2020).

Economic integration

Overall effects on the economy are estimated with a multi-sector, multi-country computable general equilibrium model. The model accounts for the direct impacts as estimated by the specific impact models as well as the additional indirect effects in the economy due to the cross-sectoral and cross-country or trade adjustments. The model uses loss estimates for the following impact categories: agriculture, energy, drought, river flooding, coastal flooding, human mortality of temperature extremes, and windstorms. The economic model transmits direct economic damage into the economic system through changes in productivity (e.g. due to lower crop yield), changes in capital stock (e.g. due to flood impacts) and changes in consumption (e.g. repairing of storm damage reduces consumption possibilities of households). The integration in the macro-economic model allows each impact to be evaluated in a uniform economic metric, consumer welfare. More details in Szewczyk et al. (2020).

3 Climate in Europe with global warming

The last five years (2015-2019) were the hottest years on record since 1850, when global average temperature started being tracked. It is currently estimated to be 1.1°C above pre-industrial times (1850-1900) and 0.2°C warmer than 2011-2015 (World Meteorological Organization, 2019). PESETA IV uses the period 1981-2010 as a reference, when global average temperature was already 0.8°C higher on average compared to pre-industrial times.

Figure 2 shows the change in annual average temperature and precipitation across Europe between the reference period and the three warming scenarios of the project. Even when limiting global warming to 1.5°C (or 0.7°C in addition to the average warming over 1981-2010) a large fraction of Europe is projected to face an increase in temperature of 1°C or more relative to the reference period. Hence, the magnitude of warming is greater than the global average and not uniform over Europe. Under the 2°C and 3°C global warming scenarios, the spatial temperature differences become more apparent, with northern Europe and parts of southern Europe showing stronger warming. With respect to precipitation, while moderate changes are projected up to 2°C, with 3°C global warming more significant differences are projected, with increases for north-central-eastern Europe and a decline for most parts of the Mediterranean.

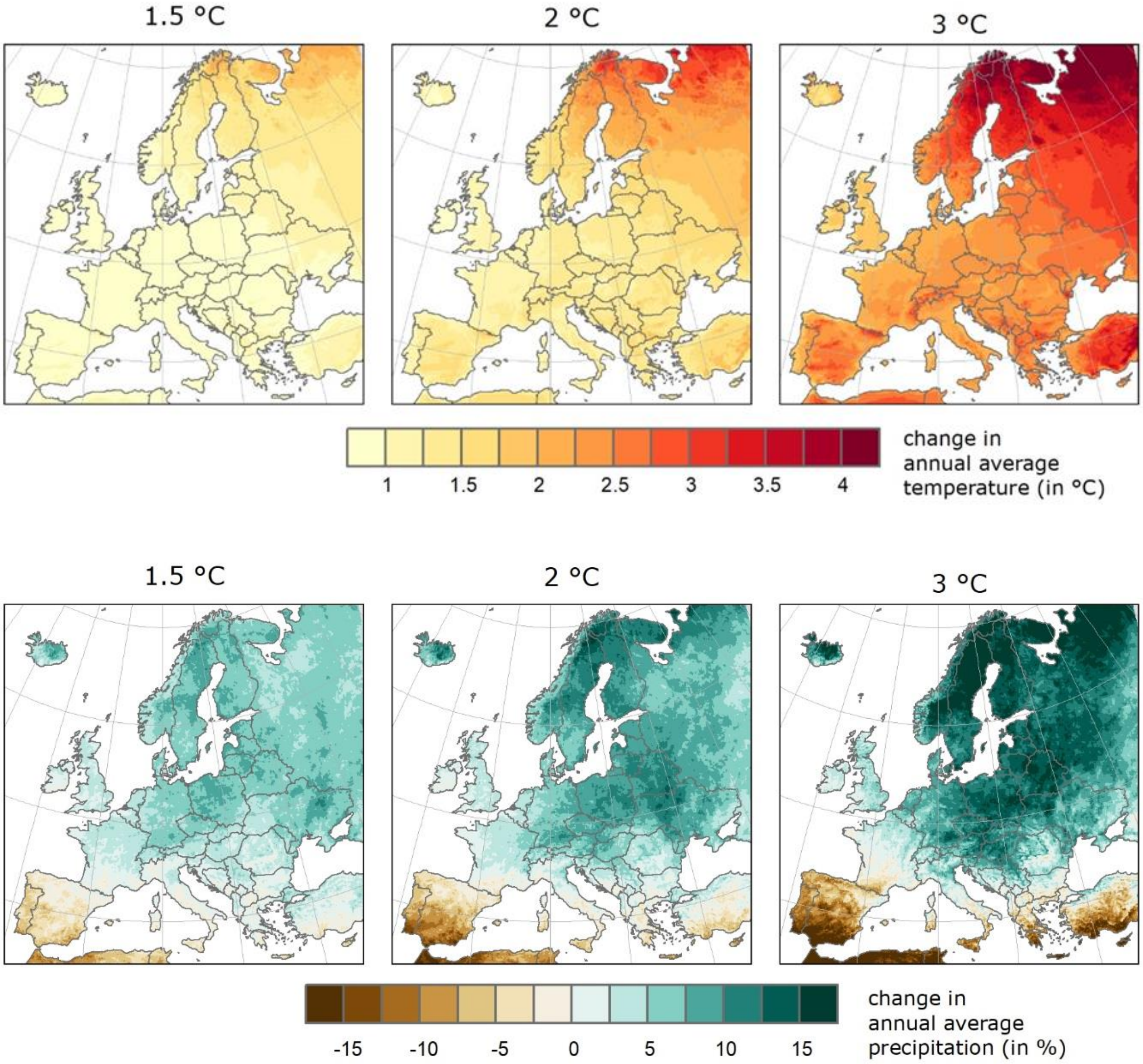


Figure 2. Changes from reference (1981-2010) in annual average temperature (top panels) and precipitation (bottom) for the three global warming scenarios used in PESETA IV (1.5°C, 2°C and 3°C warmer than pre-industrial times).

Figure 3 presents the average summer temperature and precipitation changes with respect to the reference period. The projected increase in summer temperature is stronger especially in southern parts of Europe compared to the increase in annual average temperature. In the most northern parts of Europe warming in summer is somewhat less compared to the rise in annual average temperature. The increase in summer precipitation in northern Europe is also less strong than that in annual terms, while the decrease in summer precipitation in southern Europe is much stronger (up to 30%) compared to that on an annual basis (up to 15%). Summer precipitation is also projected to decline in western Europe and parts of central and eastern Europe, even when annual average precipitation is projected to increase. More details on projected climate in the EU for different warming levels can be found in Dosio et al. (2020).

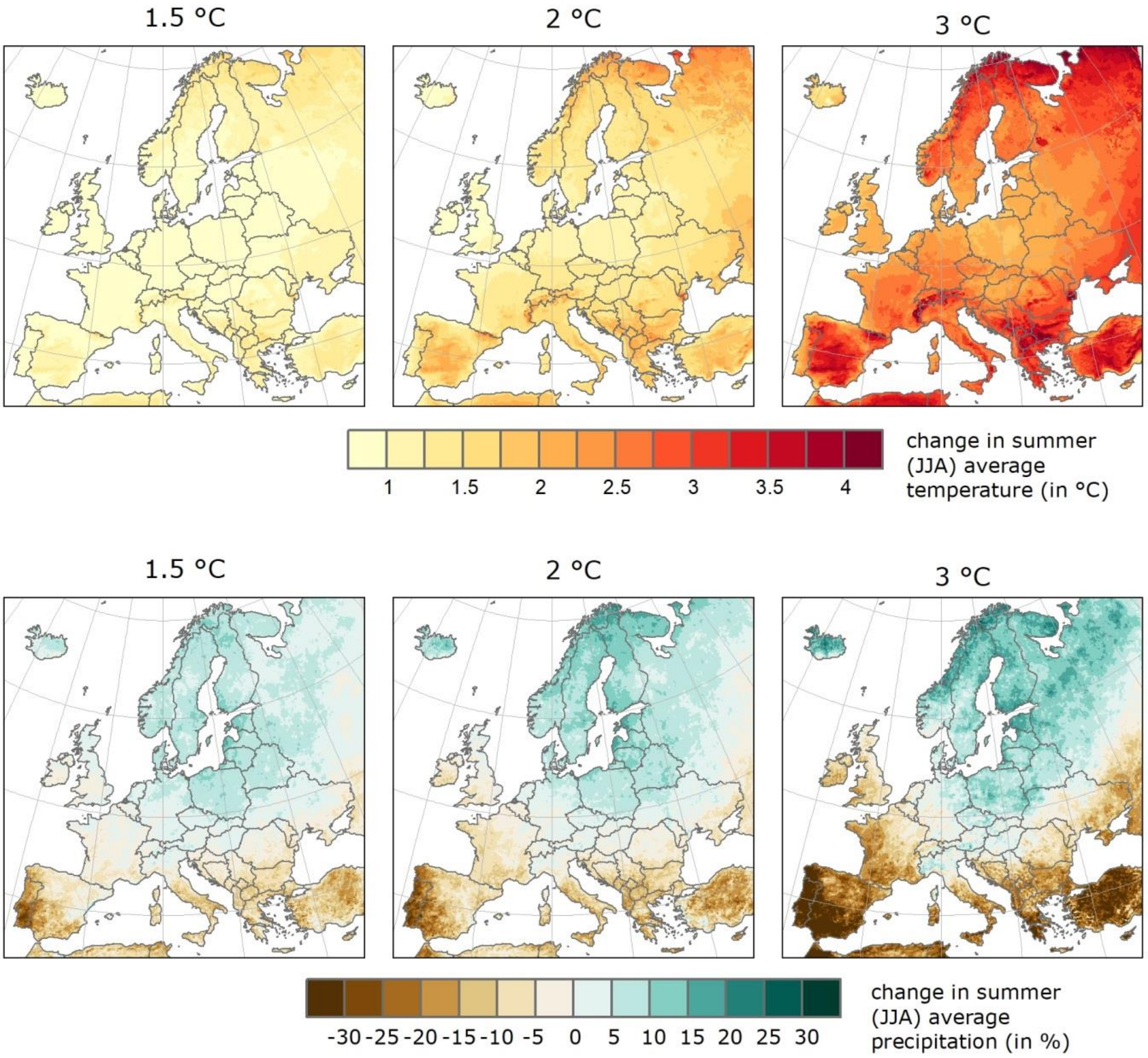


Figure 3. Changes from reference period (1981-2010) in summer temperature (top panels) and precipitation (bottom) for the three global warming scenarios used in PESETA IV (1.5°C, 2°C and 3°C warmer than pre-industrial times).

Figure 4 represents the changes in average temperature and precipitation for the winter season. Milder winter temperatures under the 3°C scenario are mainly projected for northern and eastern Europe. Winters will generally be wetter in most of Europe, except for the most southern parts of Europe where reductions up to 25% in winter precipitation are projected.

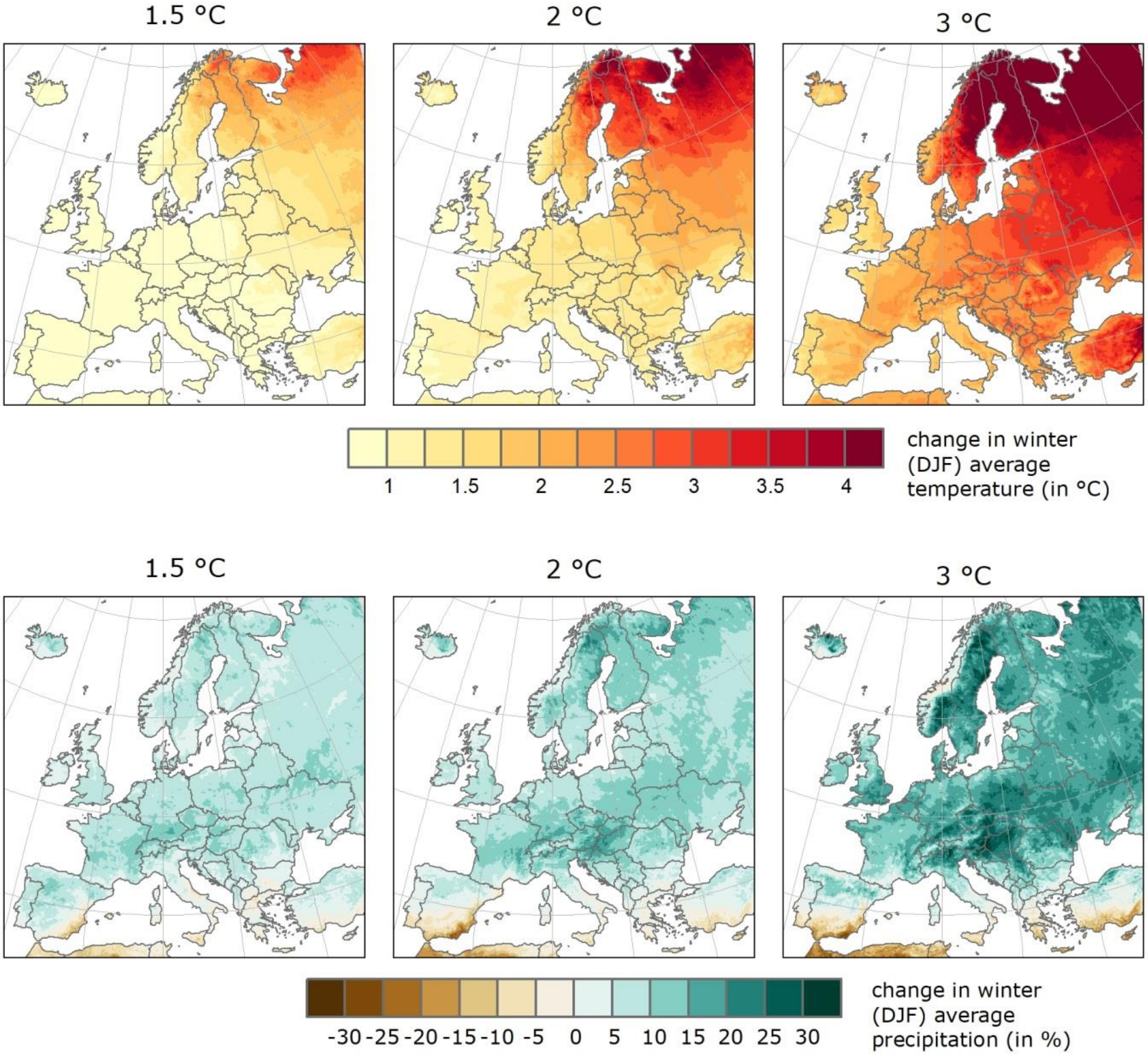


Figure 4. Changes from reference (1981-2010) in winter temperature (top panels) and precipitation (bottom) for the three global warming scenarios used in PESETA IV (1.5°C, 2°C and 3°C warmer than pre-industrial times).

4 Human impacts from heat and cold extremes

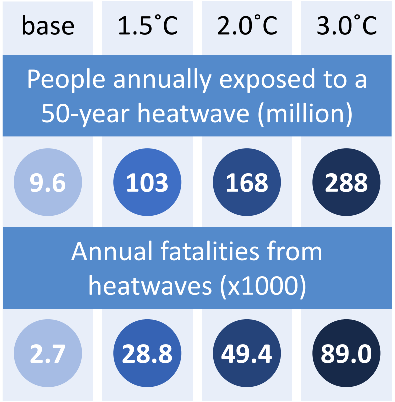
During intense heatwaves this summer (June and July 2019), all-time temperature records tumbled in many locations in Europe. These events are expected to happen more frequently and become more intense with climate change. If temperatures could be stabilised with 1.5°C, each year more than 100 million Europeans would be exposed to a present intense heatwave (this is a heatwave that under present climate is expected to happen once every 50 years), compared to around 10 million/year now (1981-2010). With 2°C, this increases to 176 million people per year and with unmitigated climate change (3°C in 2100) to nearly 300 million/year, or more than half of the European population. Without climate mitigation and adaptation, the death-toll from extreme heat in the EU could be more than 30 times more than at present by the end of this century. The rise in exposure to and deaths from extreme heat is most pronounced in southern Europe. Milder winters will reduce significantly exposure to and deaths from extreme cold.

Current effects of heat and cold extremes

Spells of several consecutive days of unusually high or cold temperatures can have a considerable impact on people. Since 1980, heat and cold waves have caused nearly 90,000 fatalities in Europe. A large majority of these reported fatalities from temperature extremes relate to heatwaves. The more vulnerable are older people and those with diseases who have reduced physiological and behavioural capacity for thermoregulation, as well as the poor who have less access to technological means for private extreme temperature mitigation (e.g. through air conditioning or thermal insulation).

Projections of future heat and cold extremes

Global warming will progressively increase the frequency and severity of heatwaves and result in a gradual decline in the intensity and frequency of extreme cold spells. Both trends are very strong across the EU, but are somewhat more pronounced in southern European countries. In a 3°C warmer climate compared to pre-industrial times, a current 50-year heatwave may occur almost every year in southern Europe, whereas in other regions of Europe such events may happen every 3 to 5 years.



base	1.5˚C	2.0˚C	3.0˚C
People annually exposed to a 50-year heatwave (million)			
9.6	103	168	288
Annual fatalities from heatwaves (x1000)			
2.7	28.8	49.4	89.0

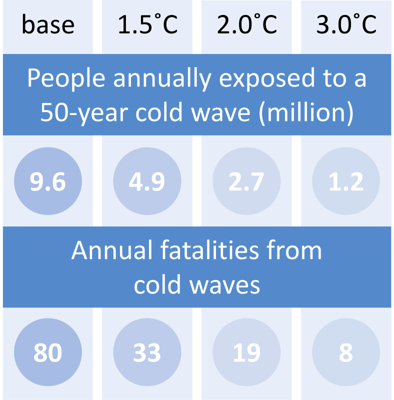
Figure 5. Human exposure to and fatalities from heatwaves in Europe.

Future effects of heat and cold extremes

The projected changes in heatwave hazard leads to a large increase in the number of people exposed to extreme heat with global warming (Figure 5). Even when temperatures could be stabilised with 1.5°C, each year more than 100 million Europeans are expected to be exposed to a present 50-year heatwave intensity, compared to nearly 10 million/year under baseline climate conditions (1981-2010). With 2°C, this grows to nearly 170 million/year. With unmitigated climate change (3°C in 2100), the number of people annually exposed to this intensity of heat climbs to nearly 300 million per year, meaning that more than half of the European population could be exposed each year to a present 50-year heatwave.

Assuming present vulnerability and no additional adaptation, annual fatalities from extreme heat could rise from 2,700 deaths now to nearly 30,000 with 1.5°C global warming, 50,000 with 2°C and 90,000 with 3°C. The increase in human exposure to and fatalities from extreme heat is most pronounced in southern European countries and the highest number of fatalities will occur in France, Italy and Spain.

Conversely, milder winters significantly reduce exposure to and fatalities from extreme cold. The population expected to be annually exposed to a present 50-year extreme cold (i.e., a cold wave that is expected to happen once every 50 years in present climate conditions) is projected to decrease from approximately 10 million in the baseline to reach 5 million with 1.5°C (50% reduction), 2.7 million with 2°C (60% reduction) and 1.2 million with 3°C (>80% reduction) (Figure 6). The number of reported fatalities associated with extreme cold spells in recent years is already much smaller than those from heatwaves (100 fatalities/year over the period 1980-2016). This will further drop as a result of global warming.



base	1.5˚C	2.0˚C	3.0˚C
People annually exposed to a 50-year cold wave (million)			
9.6	4.9	2.7	1.2
Annual fatalities from cold waves			
80	33	19	8

Figure 6. Human exposure to and fatalities from cold spells in Europe.

Total effect of climate change on temperature-related premature mortality

The contribution of extreme temperatures to the overall temperature-related excess mortality is relatively small. Hence, although global warming will result in a strong net increase in exposure to and fatalities from temperature extremes, this only captures part of the effects of climate change on temperature-related premature deaths. The mortality burden attributable to non-extreme below-optimum ambient temperature (i.e. temperatures below the optimal temperature for human health but not necessarily extremely cold) will likely decrease with global warming, while fatalities linked to non-extreme above-optimum temperatures (i.e. temperatures above the optimal temperature for human health but not necessarily extremely hot) will increase. As currently most of the temperature-related mortality can be attributed to non-extreme below-optimum temperatures (cold) it is unclear what the net effects of climate change will be on total premature temperature-related human mortality.

Socioeconomic drivers of future human risk of heat and cold extremes

Population ageing in Europe is a major demographic trend for the coming decades. It could further increase the effect on human beings of temperature extremes. Further, increasing urbanisation could amplify the urban heat island effect, which causes urban and metropolitan areas to be significantly warmer than their surrounding rural areas. The combined effects of heatwaves and air pollution might further exacerbate human stress in densely populated areas.

Adaptation to temperature extremes

Even with stringent mitigation action and limiting global warming to 1.5°C or 2°C, the rise in people exposed to extreme heat could be manifold. Hence, societies will need to increase their resilience to cope with more frequent and intense heatwaves. There exist a wide range of adaptation measures, including improved design and insulation of houses, schools and hospitals, education and awareness raising of potential risk factors and recommended responses, and early warning systems. It is also important to consider other impacts of extreme temperature on ambient air quality, such as ozone pollution under heatwaves, in order to identify the most appropriate response. In the medium to long term (5 to 15 years and over 15 years respectively)[1], sound urban planning should aim to minimise the urban heat island effect. This can be achieved, for example, by increasing tree and vegetative cover, installing green or reflecting roofs, or using cool pavements (either reflective or permeable). There is a substantial lack of observations and quantitative information on the effectiveness of these measures, yet several of them can provide important co-benefits, such as reduced energy-demand of thermo-efficient buildings, or water retention and mental health benefits of green spaces.

Approach

The PESETA IV task on human impacts of heat and cold extremes provides a quantitative assessment of human exposure to and mortality from these extremes in Europe. The methodology integrates empirical data on human losses from disasters, past climate information, EUROSTAT demographic data and high resolution climate and socio-economic projections. As is common to all PESETA IV impact categories, the analysis first evaluates heat and cold wave mortality in a comparative static socio-economic setting, therefore only considering the influence of the climate change signal. This is done by comparing impacts on the present population under the baseline climate (1981-2010) and climate with 1.5°C, 2°C and 3°C global warming above preindustrial levels. In addition, we also provide a dynamic socio-economic assessment considering the 2015 Ageing Report projections of population, and look at how heat and cold extremes at the different warming levels would impact EU population projected for 2050 and 2100. As a 3°C warming scenario is unrealistic by mid-century, only the Paris targets are considered in 2050. Our impact estimates assume that the mortality rates that have been derived from recent disaster loss records remain unchanged, hence they do not consider adaptation. More details in Naumann et al. (2020).

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[1] As defined by CoMO (2016). Mayors Adapt - Reporting Guidelines. Brussels: Covenant of Mayors Office.

5 Impacts of windstorms

Windstorms are amongst the most damaging natural hazards in Europe, with approximately 5 €billion of estimated annual losses in the EU. The number of reported windstorms has increased significantly over the last decades, yet there is no consensus about a climate-induced trend in windstorms over Europe. Climate model projections of extreme winds suggest that windstorms will not become more intense or happen more frequently with global warming over most of the European land. As a consequence, it is expected that risk from windstorms in the EU will not rise due to climate change. In case of no adaptation, economic loses from extreme winds will rise due to increasing asset values. Impacts of wind extremes could be reduced by a range of measures, such as the development and implementation of enhanced windstorm-resilient standards and building codes.

Current effects of windstorms

During the last few decades, Europe was hit by a number of highly damaging windstorms that caused a considerable human and economic impact, ranging from human fatalities and injuries to damage to roads, power plants, the agriculture sector, forests, infrastructure, and private properties. Estimated average annual losses for EU and UK amount to 5 €billion/year (in 2015 values), or approximately 0.04% of total GDP (of 2015). Absolute losses are highest in Germany (850 €million/year), France (680 €million/year), Italy (540 €million/year) and the UK (530 €million/year), while impacts relative to the size of the economy are double the EU average in Bulgaria and Estonia (0.08% of GDP), and 0.07% of GDP in Latvia, Lithuania and Slovenia. Each year approximately 16 million EU citizens are exposed to windstorms with an intensity that happens only once every 30 years in the present climate, resulting in nearly 80 annual deaths. While in tropical regions an increase in the frequency and intensity of cyclones has been observed in the last decades, in particular from the 1990's, in Europe there is no robust trend in windstorms.

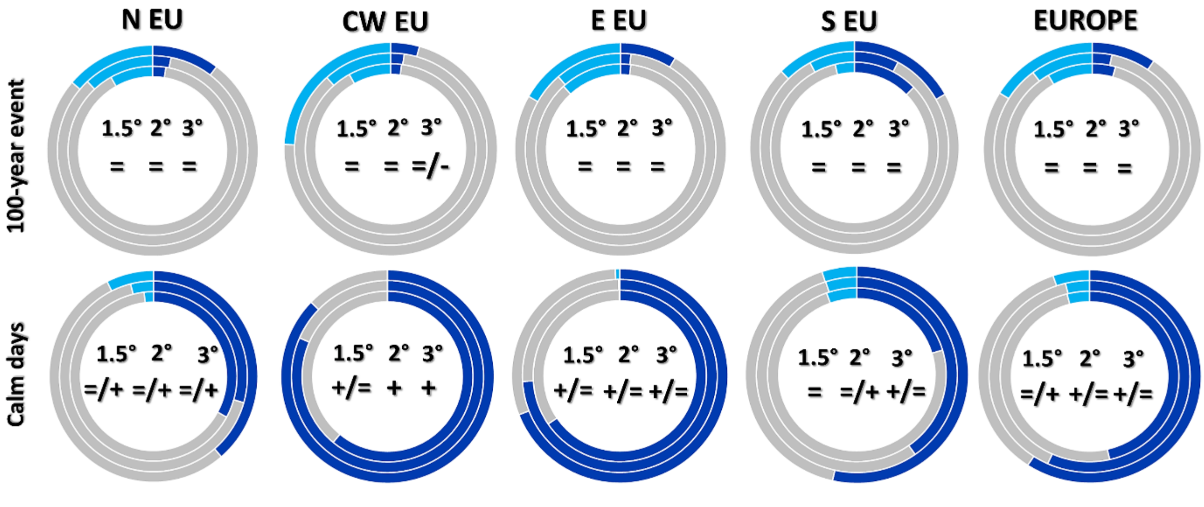


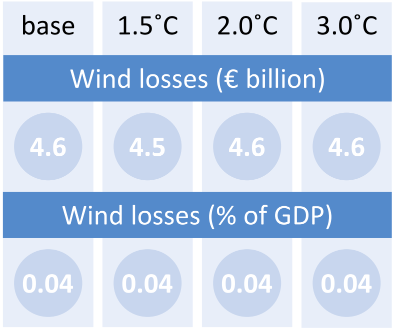
Figure 7. Area fraction (in %) of each region (northern Europe, central-western Europe, eastern Europe, southern Europe) with a significant increase (dark blue), no change (grey) and decrease (light blue) in 100-year wind speed (change is significant if > 0.3 m/s and 2/3 models agree on sign of change) and number of calm days (change is significant if > 5 days and 2/3 models agree on sign of change). Inner (outer) circle represents 1.5°C (3°C) warming.

Wind hazard across Europe in a warmer climate

Present climate model projections suggest small changes in wind hazard with global warming in Europe. With 3°C warming, maximum wind speeds will likely reduce over 16% of the land area, increase over nearly 10% and remain relatively stable over the rest of Europe. Southern Europe is the region with the largest share of the area with an increase in wind extremes (17% with 3°C), while central-western Europe has the largest share of land for which less intense wind extremes are projected (24% with 3°C). Also the number of windy or stormy days does not show significant changes. On the other hand, there is a robust tendency projected towards more calm days (daily maximum wind speed below 3.5 m/s) over most of Europe, in particular over central, western and eastern Europe (Figure 7).

Economic losses from windstorms assuming no socioeconomic change

The lack of a significant trend in wind hazard with global warming across Europe implies that human and economic impacts in the EU will remain stable when assuming that current socioeconomic conditions continue into the future (Figure 8). For most countries impacts remain stable, although losses could grow to 0.08% of the country GDP (of 2015) in Hungary, Romania and Slovakia with 3°C global warming, compared to 0.06% under the present climate. In Estonia, on the other hand, losses could drop from 0.08% of GDP under present climate to 0.05% of GDP with 3°C global warming.

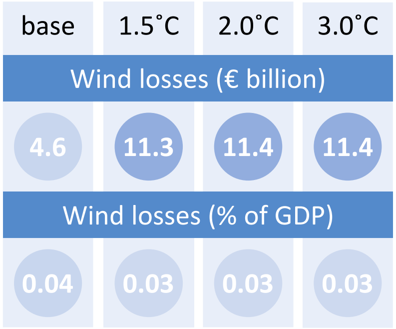


	base	1.5˚C	2.0˚C	3.0˚C
Wind losses (€ billion)	4.6	4.5	4.6	4.6
Wind losses (% of GDP)	0.04	0.04	0.04	0.04

Figure 8. Annual wind losses for the EU and UK assuming that current socioeconomic conditions continue into the future.

Economic losses from windstorms with socioeconomic change

The projected losses in absolute terms are larger when future socioeconomic change is accounted for compared to when the current socioeconomic conditions are assumed to continue into the future, because of the growth of the size of the economy and hence higher values of the exposed assets. By 2050, windstorm annual losses are projected to grow to nearly 7 €billion/year (in 2015 values) for both 1.5°C and 2°C global warming. By the end of this century this further grows to more than 11 €billion/year, with slightly higher impacts for higher levels of warming (Figure 9). Future wind-induced damage expressed as a share of the size of future economies show a small decrease because building stock and replacement costs grow somewhat slower than GDP.



	base	1.5˚C	2.0˚C	3.0˚C
Wind losses (€ billion)	4.6	11.3	11.4	11.4
Wind losses (% of GDP)	0.04	0.03	0.03	0.03

Figure 9. Annual wind losses for the EU and UK assuming socioeconomic conditions in 2100 according to the ECFIN Ageing Report.

Resilience to wind extremes

Even though our projections indicate that wind hazard and risk are unlikely to change in Europe with global warming, increasing resilience to present wind extremes could further reduce impacts on future societies. There are a wide range of measures that could be taken, such as increasing windstorm forecast accuracy and warning time, improving storm readiness, emergency communications and response, as well as structural measures for wind-proofing infrastructures, which in the EU could be stimulated by amendments of Eurocodes.

Approach

Projections of daily wind speed under a high emissions scenario (RCP8.5) and moderate mitigation scenario (RCP4.5) were used in order to estimate changes in wind hazard between baseline (1981-2010) climate and at global warming levels of 1.5°C, 2°C and 3°C above preindustrial levels. Wind damage functions, which relate the total construction stock with wind speed and economic losses, as well as reported fatalities, were derived from past wind events and their reported impacts. In the absence of information on future vulnerability, these impact relations were kept constant in the scenarios. The damage and mortality relations were then applied in a static-economic scenario, in which wind hazard at the different warming levels was applied to the present population and construction stock. We also combined the projections of wind hazard at the warming levels with projections of exposed construction assets and population in 2050 and 2100 according to the ECFIN Ageing Report. As it is very unlikely that 3°C warming will happen by mid-century, this warming level was only combined with 2100 society in the dynamic economic scenario. The use of the static and dynamic economic scenarios allows disentangling the effects of climate change and exposure dynamics on future windstorm losses.

An important limitation of the analysis is the spatial resolution of the wind data, which is too coarse to capture severe local windstorms. The current generation of climate models also have a rather poor physical representation of wind dynamics. Further, in the absence of wind gust data at sub-daily time steps we used daily maximum wind speed as a proxy of windstorms. It is yet unclear if these limitations affect current projections of wind hazard in view of global warming. More details in Spinoni et al. (2020).

6 Impacts on water resources

The long-term imbalance resulting from water demand exceeding available renewable water resources is an increasingly frequent and widespread phenomenon in the EU. The number of people in the EU and UK who are living in areas that are considered to be under water stress for at least one month per year could rise from 52 million nowadays to 65 million in a 3°C warming scenario, which is equivalent to 15% of the EU population. In general, climate projections reveal a north-south pattern across Europe for water availability. Overall, southern European countries, which already suffer most from water scarcity, are projected to face decreasing water availability, particularly Spain, Portugal, Greece, and Italy. Mitigation alone is not enough to avoid adverse climate change impacts and adaptation strategies will be needed too.

Water scarcity is already an issue in the EU

There are currently around 52 million people in the EU and UK living in water scarce regions. This is equivalent to 11% of the population. Most of the people exposed to water stress live in countries in southern Europe, including Spain (22 million; 50% of the national population), Italy (15 million; 26%), Greece (5.4 million; 49%) and Portugal (3.9 million; 41%). The entire populations of Cyprus and Malta are considered to be living in water scarcity. In the Mediterranean the period of water stress can exceed 5 months (Figure 10). During summer, water exploitation in this region can be close to 100%, meaning that all possible water is being used, and often also a substantial amount of fossil groundwater.

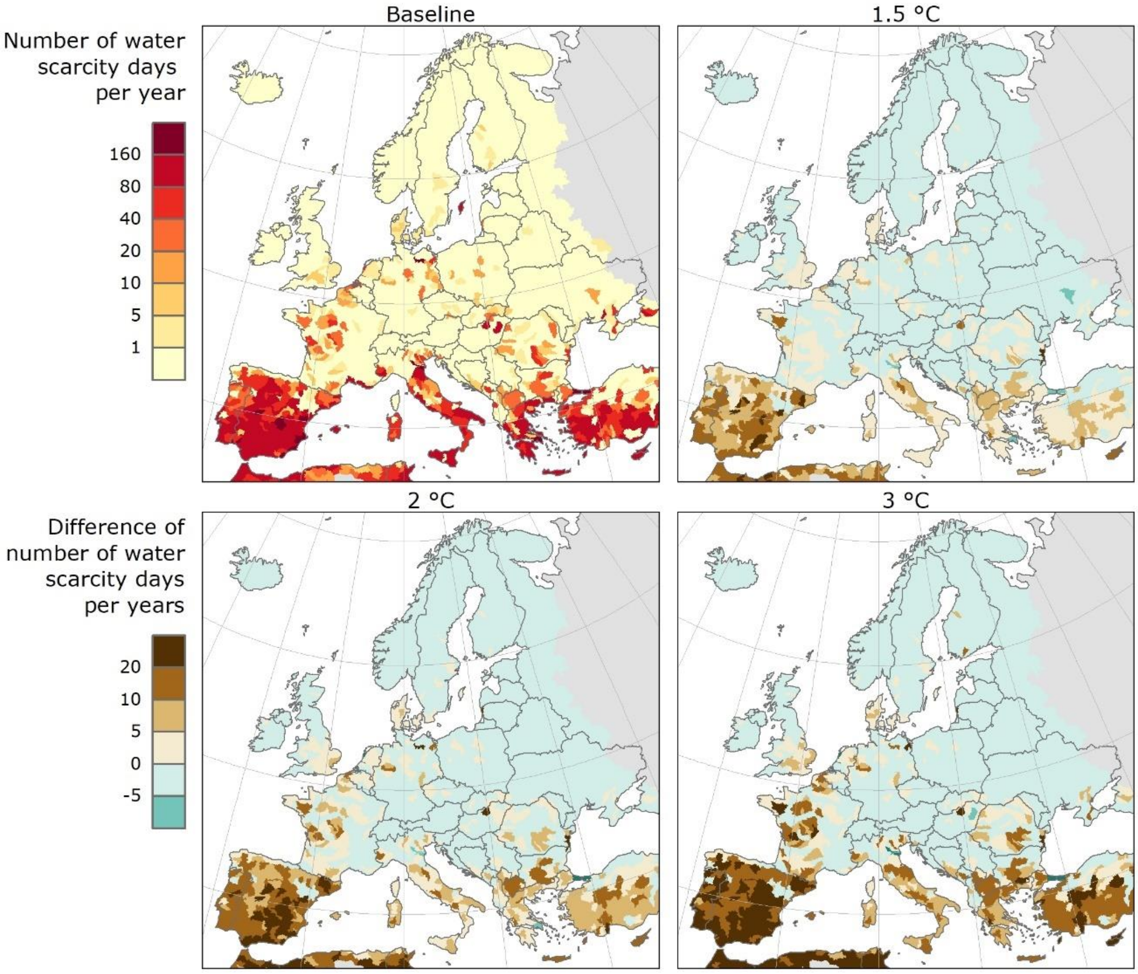


Figure 10. Number of water scarce days (WEI+ greater than 0.2, see Approach) in reference period and projected changes in with global warming.

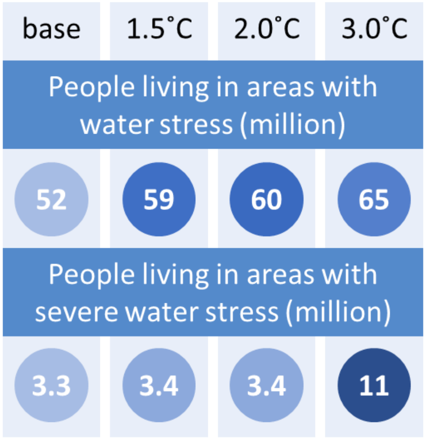
Current pressures on water resources are exacerbated in southern Europe

A clear north-south pattern of change in water stress is projected with global warming. Water scarcity conditions will worsen in regions that already face water stress now. The number of days with conditions that are considered to represent water stress increases sharply around the Mediterranean region with increasing global warming (Figure 10). In the Iberian Peninsula water scarce days can increase by up to more than one month per year in the 3°C warming scenario relative to present. Areas that will increasingly face water stress with warming also emerge in countries further north like the UK, Belgium, the Netherlands, Germany, Denmark, Bulgaria, Romania and France. Other central and northern European countries show a trend towards increasing water availability with global warming.

Population exposed to water scarcity due to climate change

The number of people living in areas with water resources under stress increases to 65 million with 3°C global warming. This is 13 million (+25%) more than at present, with nearly 8 million people more living in areas with severe conditions of water stress, or nearly four times more than at present. Limiting global warming to 1.5°C would halve the increase in number of people living in water scarce areas and effectively avoid any additional people facing severe or unsustainable water stress (Figure 11).

Spain sees the largest absolute increase in the number of people living in areas with water resources under stress. In the 3°C warming scenario these amount to over 7 million more that at present. In Greece the number of people facing water stress would grow with by 3.5 million to nearly 9 million with 3°C warming, or about 80% of the present population.



base	1.5˚C	2.0˚C	3.0˚C
People living in areas with water stress (million)			
52	59	60	65
People living in areas with severe water stress (million)			
3.3	3.4	3.4	11

Figure 11. Population in EU and UK living in areas with water stress (WEI+ > 0.2, see Approach) and severe (WEI+ > 0.4) water stress for different levels of global warming.

Socioeconomic drivers of water scarcity

Climate change is the main driver of increasing water stress in southern Europe. Demographic changes, land use dynamics and corresponding water usage variations play a minor role. In general the additional number of people exposed to water scarcity is somewhat higher compared to the static population scenario due to projected population growth in countries exposed to water stress (e.g. France). The number of people exposed to severe water shortage is slightly lower when accounting for demographic trends due to a projected decline in population in countries also exposed to severe water limitations (e.g. Greece). Projections of economic growth everywhere in EU result in a strong increase in economic activity exposed to water stress.

The need for adaptation

The severity of some of the projected changes in water availability suggests that various adaptation mechanisms will be needed to lessen the effects on population and economic activities exposed to water scarcity, even under lower magnitudes of warming. In some regions, projected increases in water dependency on upstream water requires further water diplomacy efforts between countries as well as international multi-member-state management of river basin water resources. In the EU, this is already operational under the Water Framework Directive and in various River Basin Commissions, such as for the Danube, Rhine, Elbe, Meuse, Oder, Sava and others.

Adaptation could be targeted at demand-driven scarcity, rather than increasing supply, as this may further increase water dependency. Supply side measures also have known detrimental environmental effects (reservoirs) or increased energy requirements (desalination). Imbalanced water demand can only be alleviated in a sustainable manner by lowering water dependency in water-intensive sectors. Water pricing could create an incentive for users to consider water savings and develop water-conserving technologies. Among the wide range of possible measures, this includes for example, increasing irrigation efficiency by changing irrigation methods (e.g. from sprinkling to drip irrigation), or shifts to crops with lower water requirements. Furthermore, sub-optimal irrigation strategies may lead to substantial water savings with only limited reductions in crop yield. Other options include more efficient cooling technologies that lead to a reduction in water use for producing energy. In addition, shifts from conventional energy production (fossil fuel) to renewable energy production (wind and solar) could reduce cooling water demand and net water consumption.

Approach

PESETA IV estimated the impact of climate change on water availability using the same hydrological model that was used elsewhere in the project to assess drought, river flooding, and energy supply impacts. The LISFLOOD hydrological and water use model was forced by climate projections for a high emissions (RCP8.5) and moderate-mitigation (RCP4.5) scenario to simulate river flow for present climate and climate with 1.5°C, 2°C and 3°C global warming above preindustrial levels. The Water Exploitation Index (WEI+), or withdrawal ratio, is a metric of water stress that is defined as the percentage of total renewable freshwater resources used in a defined territory in a given period. The WEI+ takes into account inflowing river water from cross-border river basins. It was calculated at monthly scale. WEI+ values have a range between 0 and 1. Values above 0.2 indicate that water resources are under stress, while values above 0.4 indicate severe stress and an unsustainable use of freshwater resources. PESETA IV estimated population exposure to water stress for the baseline and 1.5°C, 2°C and 3°C global warming by calculating the number of people living in areas with an average annual WEI+ larger than 0.2, and above 0.4 for severe water stress. Water stress exposure was estimated under two main assumptions of socioeconomic change: 1) a continuation of present conditions into the future; and 2) socioeconomic development according to the ECFIN Ageing Report. More details in Bisselink et al. (2020).

7 Impacts of droughts

Droughts induce a complex web of impacts that span many sectors of the economy, as exemplified by extensive crop failure, reduced power supply, and shipping interruptions in the EU during 2018 and 2019. With global warming droughts will happen more frequent, last longer and become more intense in southern and western parts of Europe, while drought conditions will become less extreme in northern and north-eastern Europe. With 3°C global warming in 2100 drought losses could be 5 times higher compared to today, with the strongest increase in drought losses projected in the Mediterranean and Atlantic regions of Europe. When expressed with respect to the total size of the economy the effects are dampened relatively, because drought-sensitive sectors like agriculture are projected to become relatively less economically prevalent in future EU economies than they are nowadays. The consequences on ecosystems are typically not monetized and hence are not reflected in the loss estimates.

Current economic losses from drought

PESETA IV estimates current annual losses from drought to be around 9 €billion for the EU and UK, with the highest losses in Spain (1.5 €billion/year), Italy (1.4 €billion/year) and France (1.2 €billion/year). Depending on the region, between 39-60% of the losses relate to agriculture and 22-48% to the energy sector. Public water supply accounts for between 9-20% of the total damage. Losses in the transport sector relate only to inland water transportation and on average represent 1.5% of total losses, while subsidence damage to infrastructures accounts for around 8% of total losses. Drought also affects the environment in many different ways, yet these impacts are difficult to valuate.

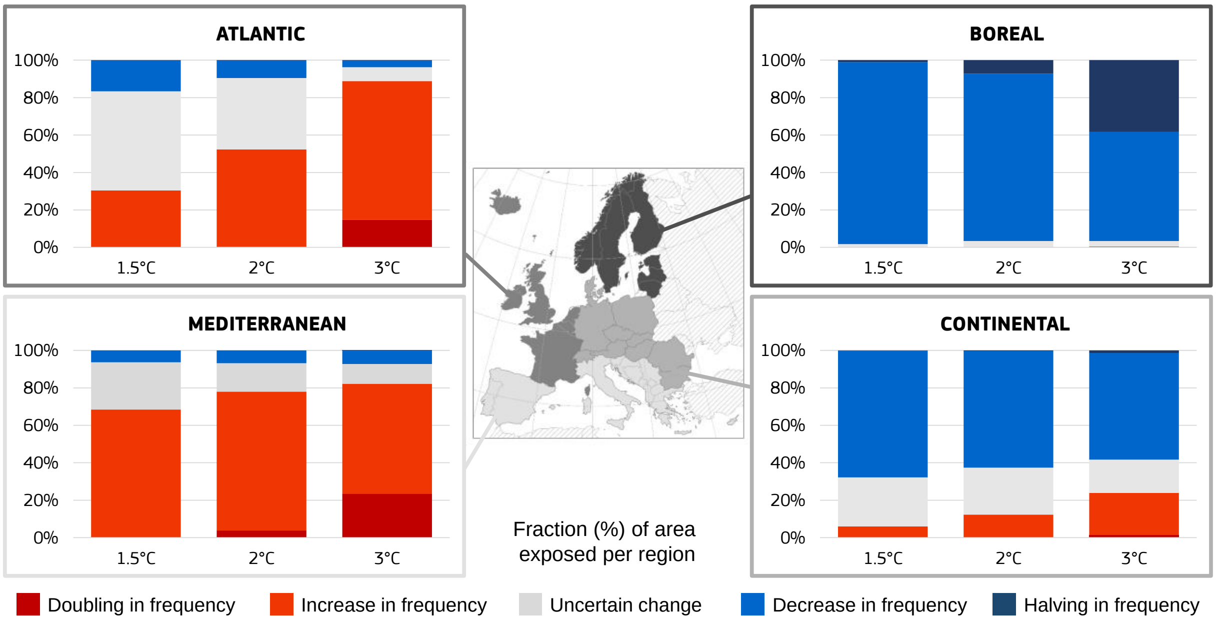


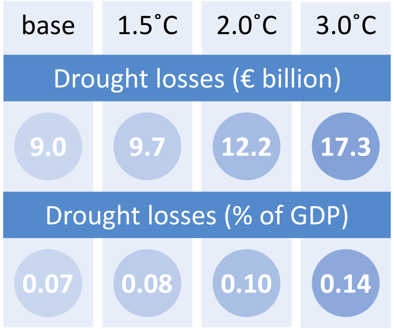
Figure 12. Fraction of area exposed to changes in drought occurrence compared to 1981-2010 for European sub-regions.

Drought hazard across Europe in a warmer climate

Hydrological droughts will progressively happen more frequently and intensify in Mediterranean and Atlantic European regions with global warming. Drought conditions will also worsen in southern parts of the Continental region. With 3°C warming drought frequency is projected to double over nearly 25% of the Mediterranean and 15% Atlantic region. Limiting global warming to 1.5°C would still result in an increase in drought frequency over two-thirds of the Mediterranean and one-third of the Atlantic region, but would avoid a doubling of drought frequency everywhere in Europe (Figure 12). In contrast, in Boreal Europe and the north-eastern parts of Continental Europe drought hazard will decline due to increasing precipitation with climate change. In central and eastern Europe the projected trends show more climate variability and are more uncertain.

Economic losses from droughts assuming no socioeconomic change

If future climate would act on today's society, total EU and UK drought damage slightly increases with global warming of 1.5°C (9.7 €billion/year) but then increases stronger with further warming to reach 17.3 €billion/year at 3°C (Figure 13). The Mediterranean and Atlantic regions see the largest losses from global warming (Figure 14), with Belgium, Greece, Ireland, Portugal and the UK showing the strongest increase in losses relative to now. Countries in Atlantic and especially Mediterranean Europe already suffer the highest drought impacts. These regions contribute to 68% of the total European losses in the recent past and their share progressively increases with warming and could grow to 85% at 3°C warming. Drought losses will also increase in the most southern countries of Continental Europe (Bulgaria and Romania).



base	1.5˚C	2.0˚C	3.0˚C
Drought losses (€ billion)			
9.0	9.7	12.2	17.3
Drought losses (% of GDP)			
0.07	0.08	0.10	0.14

Figure 13. Average annual losses from drought for the EU +UK assuming that current socioeconomic conditions continue into the future.

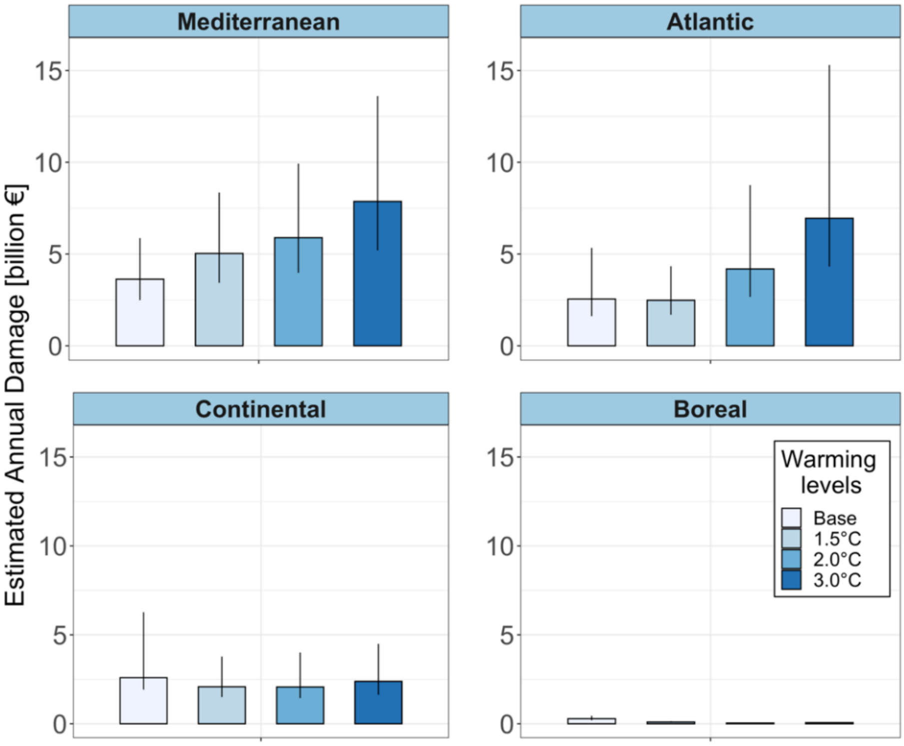
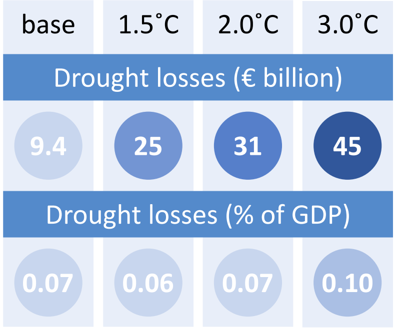


Figure 14. Current annual losses (EAD, € billion/year, 2015 values) and with global warming for EU countries + UK by region, assuming that current socio-economic conditions continue into the future. The top of each bar shows the average estimate and the vertical lines indicate climate uncertainty.

Economic losses from droughts with socioeconomic change

The projected losses in absolute terms are larger when future socioeconomic change is accounted for compared to when it is assumed that current socioeconomic conditions continue into the future, because of the growth of the size of the economy. By the end of this century, 3°C global warming would result in drought losses of 45 €billion/year in the EU and UK, compared to 25 and 31 €billion/year for 1.5°C and 2°C, respectively (Figure 15).

When drought losses are expressed relative to the size of the economy (share of GDP) the effects of climate change are dampened compared to the absolute estimates because drought-sensitive sectors, and especially agriculture, are projected to become less economically prevalent in future EU economies. Losses from drought account for 0.06% and 0.07% of the EU+UK GDP in 2050 and 2100 under both the 1.5°C and 2°C warming scenarios respectively, and 0.1% in 2100 for 3°C warming, compared to 0.07% nowadays. Regional and national-level relative impacts can be greater than the EU average, with losses of 0.19% of GDP in the Mediterranean for 3°C warming with 2100 socioeconomics, and in some countries even above 0.3% (e.g., Greece Bulgaria and Romania). Sector-level impacts can also be much greater, with losses to agriculture amounting to 4.6% of sector economic output at 3°C of warming.



base	1.5˚C	2.0˚C	3.0˚C
Drought losses (€ billion)			
9.4	25	31	45
Drought losses (% of GDP)			
0.07	0.06	0.07	0.10

Figure 15. Average annual losses from drought for the EU and UK assuming socioeconomic conditions in 2100 according to the 2015 Ageing Report.

Adaptation and resilience to drought

The PESETA IV drought impact projections are based on present vulnerability estimates of sectors to drought and hence assume no adaptation. There exists a wide variety of drought risk mitigation measures. Rather than supply-side measures, which can lead to higher dependence on water resources and increase drought vulnerability, adaptation should be targeted at strengthening drought resilience of society and sectors. This includes specific measures in drought-sensitive sectors, such as improved cooling techniques, drought-resistant crops, or lighter river navigation vessels, but also institutional transformations, livelihood and economic diversification, insurance and other market tools, social safety nets, monitoring and data collection, and early warning and alert systems. Evaluating the costs and benefits of investments made and policy actions taken to mitigate drought impacts remains a huge challenge. Yet, it is generally accepted that the costs of action are usually lower than the costs of inaction, and the returns from investing in ex-ante risk management actions are higher than those of investing in ex-post crisis management. The actual costs and benefits of adaptation measures will vary substantially depending on the local geographical, climate, and socioeconomic conditions.

Approach

The LISFLOOD hydrological and water use model was run using climate projections for a high emissions (RCP8.5) and moderate-mitigation (RCP4.5) scenario to simulate minimum river flow (an indicator of drought hazard) for present climate and climate with 1.5°C, 2°C and 3°C global warming above preindustrial levels. Drought hazard was estimated at high spatial resolution. Economic losses were estimated at country scale based on a statistical relationship between drought intensity and drought impact derived from reported losses of past drought events. Drought impacts were disaggregated over economic sectors based on expert-derived sector sensitivity to drought and their economic output. Losses are reported in € 2015 values and are inherently uncertain due to limited availability of data on past droughts and their impacts upon which the statistical relationship was derived. Losses were estimated under two main assumptions of socioeconomic change: 1) a continuation of 2015 conditions into the future; and 2) socioeconomic development according to the ECFIN Ageing Report. As it is very unlikely that 3°C warming will happen by mid-century, this warming level was only combined with 2100 socioeconomic conditions in the dynamic economic scenario. We present average estimates of drought losses over the ensemble of climate models and the spread due to climate uncertainty. Other sources of uncertainty due to model conceptualisation and parameterisation, and limited empirical drought loss data are not accounted for. More details in Cammalleri et al. (2020).

8 River flood impacts and adaptation

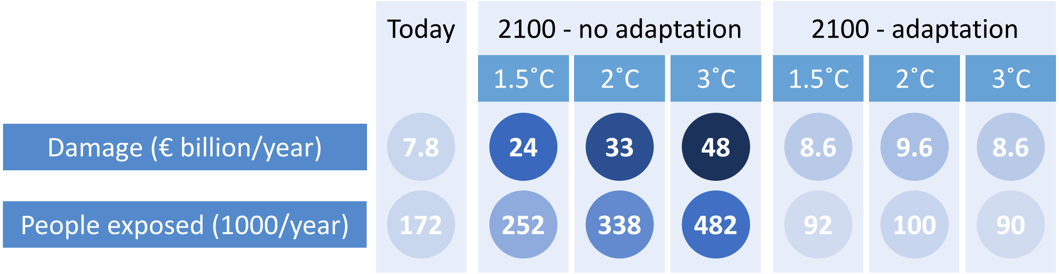
River flooding is one of the costliest natural disasters in Europe. Global warming and continued development in flood prone areas will progressively increase river flood risk. Direct damage from flooding could increase 6-fold from present losses by the end of the century in the case of no climate mitigation and adaptation. Keeping global warming well below 2°C would halve these impacts. Adequate adaptation strategies can further substantially reduce future flood impacts. In particular, reducing flood peaks using retention areas and implementing building-based damage reduction measures can lower impacts in a cost-efficient way in most EU countries, even to flood risk levels that are lower than today. Restoring natural wetlands and floodplains to retain excess water also improves the state of water and ecosystems.

Current effects of river flooding

PESETA IV estimates that at present river flooding causes damage of 7.8 €billion/year in the EU and UK, which is equivalent to around 0.06% of current GDP. Moreover, more than 170,000 people every year are exposed to river flooding.

Future impacts of river flooding without adaptation

Global warming will progressively increase flood frequency and severity in most of Europe. At the same time, the projected social and economic growth will further increase exposure to flood events. If no mitigation and adaptation measures are taken, economic losses will grow to nearly 50 €billion/year with 3°C global warming by the end of this century, or more than 6 times compared to present, while nearly 3 times as many people would be exposed to flooding. Limiting global warming to 1.5°C would halve the economic losses and population exposure to river flooding relative to unmitigated climate (Figure 16).



	Today	2100 - no adaptation			2100 - adaptation		
		1.5˚C	2˚C	3˚C	1.5˚C	2˚C	3˚C
Damage (€ billion/year)	7.8	24	33	48	8.6	9.6	8.6
People exposed (1000/year)	172	252	338	482	92	100	90

Figure 16. Annual flood damage and population exposed to river flooding for EU and UK in the present and by 2100 for different levels of global warming, with and without adaptation respectively. The “no adaptation” scenario refers to present-day flood protection measures. The “adaptation” scenario is based on the implementation of retention areas to store excess flood water to a level of protection that maximises their economic benefit.

Avoided river impacts with adaptation

Adequate flood risk reduction strategies can substantially reduce the projected increase in flood risk with global warming. In particular, reducing flood peaks using retention areas shows great potential to lower impacts in a cost-efficient way in most EU countries (Figure 18). Implementing this strategy at EU level can reduce the economic damage and population exposed by the end of the century by more than 70%, as compared to no adaptation (Figure 16). Retention areas have additional benefits, such as restoring the natural functioning of floodplain areas and improving ecosystem quality. Strengthening existing dyke systems has lower but still favourable benefit-cost ratios (Figure 17), although this can transfer risk downstream. It also tends to stimulate further development behind the flood barriers, which can result in catastrophic impacts in case of failure. Building-based flood proofing measures can also significantly reduce flood damage typically with limited implementation investments. They also do not prevent floods from happening and therefore can only partially avoid flood damage. Relocation is the least cost-effective, their implementation costs are subject to large variability and they may have lower social acceptance.

Strengthening of dyke systems:

2€ to 2.9€ saved for each € invested

41% to 68% reduction in economic damage

41% to 65% reduction in population exposed

Building of retention areas to store flood waters:

2.9€ to 3.5€ saved for each € invested

64% to 82% reduction in economic damage

63% to 81% reduction in population exposed

Damage reduction measures for buildings

5.2€ saved for each € invested

Up to 50% reduction in economic damage

No reduction in people exposed

Relocation to flood-safe areas

1.2€ saved for each € invested

17% reduction in economic damage

16% reduction in population exposed

Figure 17. Summary of the main outcomes of the analysis of four adaptation strategies considered in PESETA IV. Results are averaged at EU level and calculated considering future socioeconomic conditions (2100 economy) under 1.5°C, 2°C and 3°C warming scenarios.

The present analysis is not designed to replace detailed analyses at local and regional scale, which are necessary for an effective and reliable design and implementation of adaptation measures. On the other hand, several large European rivers are transnational, therefore our analysis can provide a consistent, pan-European framework to evaluate and compare the costs and effectiveness of river flood adaptation measures under future scenarios.

We focused our analyses on adaptation scenarios based on the application of a single type of measure. However, a combination of different measures working in synergy and optimised at the level of river basins is the best strategy to locally maximise benefits and minimise drawbacks of each measure. Moreover, the cost-benefit analysis does not include social, environmental and cultural aspects, which would require more complex multi-criteria analyses.

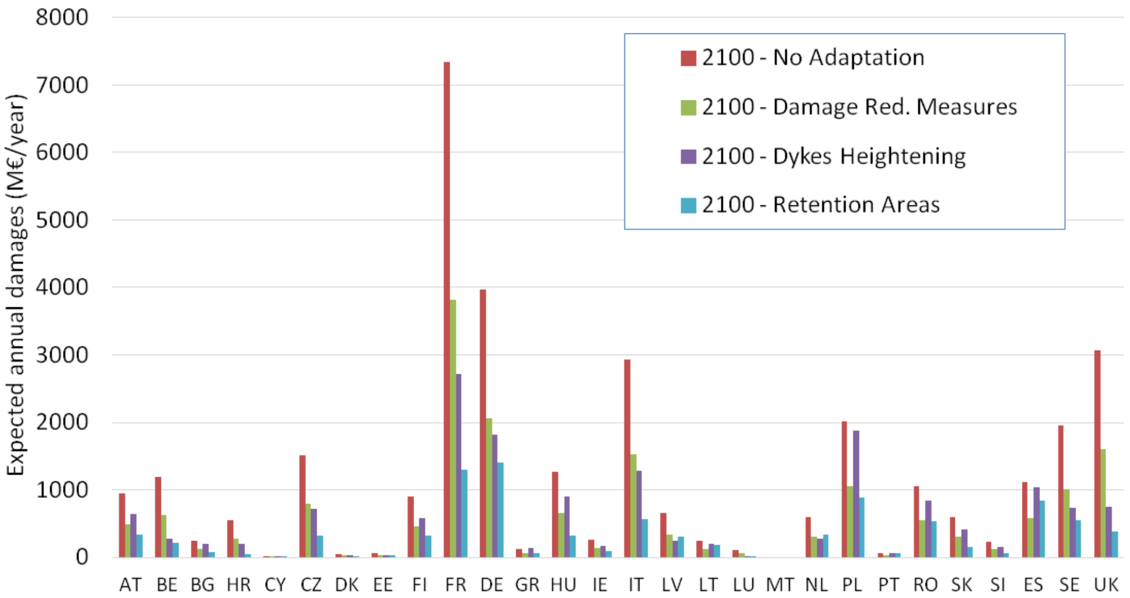


Figure 18. Comparison of expected annual damage in 2100 assuming no adaptation, and with the implementation of three different adaptation strategies. Results are calculated assuming a 2°C warming scenario.

Approach

A comprehensive modelling framework is applied to simulate river flows (LISFLOOD hydrological model), analyse the occurrence and intensity of flooding processes, and estimate the impacts on economy and people across Europe. We consider future climate scenarios corresponding to an increase of global average temperature of 1.5°C, 2°C and 3°C above preindustrial temperature, combined with socioeconomic projections according to the ECFIN Ageing Report.

We focused on four possible adaptation measures: strengthening of existing dyke systems, implementing flood damage reduction measures for buildings, building of retention areas to store flood waters, and relocation of people and buildings from flood-prone to flood-safe areas. The evaluation of each adaptation strategy is performed using a cost-benefit analysis that optimises the overall costs of implementation and avoided economic damage over the life time of the measure (up to 2100). The costs were calculated as the sum of capital investment costs to implement the measure and maintenance costs. The benefits are the damage avoided by implementing the measure, calculated as the difference between future damage with and without adaptation respectively.

Flood losses, costs and benefits are presented undiscounted in general, but in the cost-benefit analysis of adaptation future costs and benefits are discounted. The benefit-to-cost ratio, which is the ratio of total benefits to total costs, is also based on discounted values and was calculated for each NUTS2 regions and at country and EU+UK level. More details in Dottori et al. (2020).

9 Coastal flood impacts and adapation

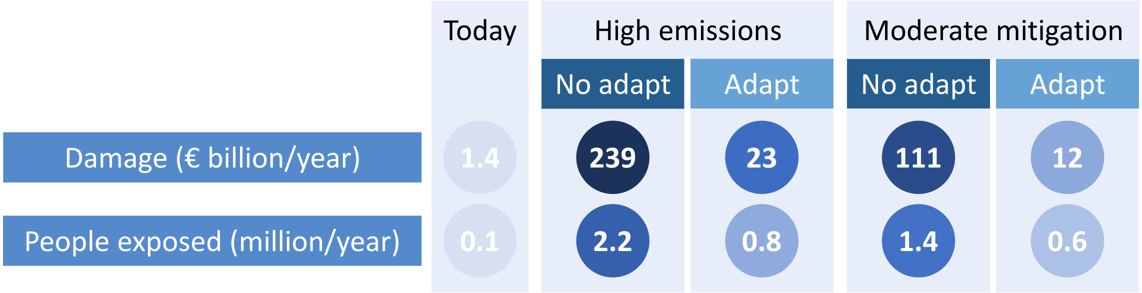
Around one third of the EU population lives within 50 km of the coast. Extreme sea levels in Europe could rise by as much as one metre or more by the end of this century. Without mitigation and adaptation measures, annual damage from coastal flooding in the EU and UK could increase sharply from 1.4 €billion nowadays to almost 240 €billion by 2100. Around 95% of these impacts could be avoided through moderate mitigation and by raising dykes where human settlements and economically important areas exist along the coastline. The extent to which adaptation can lessen the effects of coastal flooding and at what cost is sensitive to the investment strategy adopted.

Current effects of coastal flooding

Damage from coastal flooding in the EU and UK currently amounts to 1.4 €billion annually, which is equivalent to around 0.01% of current GDP. Almost half of this damage is shared by two countries: the UK (0.4 €billion annually) and France (0.2 €billion annually). Around 100,000 people are exposed to coastal flooding every year (Figure 19).

Impacts of coastal flooding without adaptation

Damage from coastal flooding is projected to rise sharply with global warming for all EU countries with a coastline and the UK if current levels of coastal protection are not raised. Annual damage grows to 239 €billion (0.52% of the EU+UK GDP projected for 2100) and 111 €billion (0.24% GDP) by 2100 under a high emissions scenario and a moderate mitigation scenario respectively (Figure 19), when assuming socioeconomic development according to the ECFIN Ageing Report. The largest absolute damage levels are projected for Germany, Denmark, France, Italy, the Netherlands and UK. For some countries the damage represents a considerable proportion of future national GDP, e.g. 4.9% (Cyprus), 3.2% (Greece) and 2.5% (Denmark) by 2100 (high emissions). Although damage from, and exposure to coastal flooding, is around 50% lower with mitigation compared with high emissions, it is still significantly greater than at present. This means appropriate adaptation measures are needed to lessen the effects of future climate change along the EU coastline.



	Today	High emissions		Moderate mitigation	
		No adapt	Adapt	No adapt	Adapt
Damage (€ billion/year)	1.4	239	23	111	12
People exposed (million/year)	0.1	2.2	0.8	1.4	0.6

Figure 19. Annual damage and population exposed to coastal flooding for EU and UK in present and by 2100 under two emissions scenarios, with and without adaptation respectively. For adaptation, dykes are raised to a level of protection that maximises their economic benefit.

Adaptation options to coastal flooding

There exists a range of adaptation measures to reduce future flood risk in coastal areas. These include natural (dunes) and artificial (dykes) structures, beach nourishment, forecasting and warning systems, flood proofing of infrastructures, and ultimately retreat from high-risk areas. Nature-based solutions, such as oyster beds, wetlands and salt marshes, create multiple benefits in addition to flood protection, such as increasing CO_2 storage, restoration of biodiversity, and offering recreational opportunities. They can also grow over time through the trapping of sediments and, thereby, compensate for rising sea levels. However, the projected rises in sea level extremes are so pronounced along Europe's coastlines that where human life may be at risk and high density, high value conurbations exist, the use of hard defence elements (dykes) will likely be unavoidable.

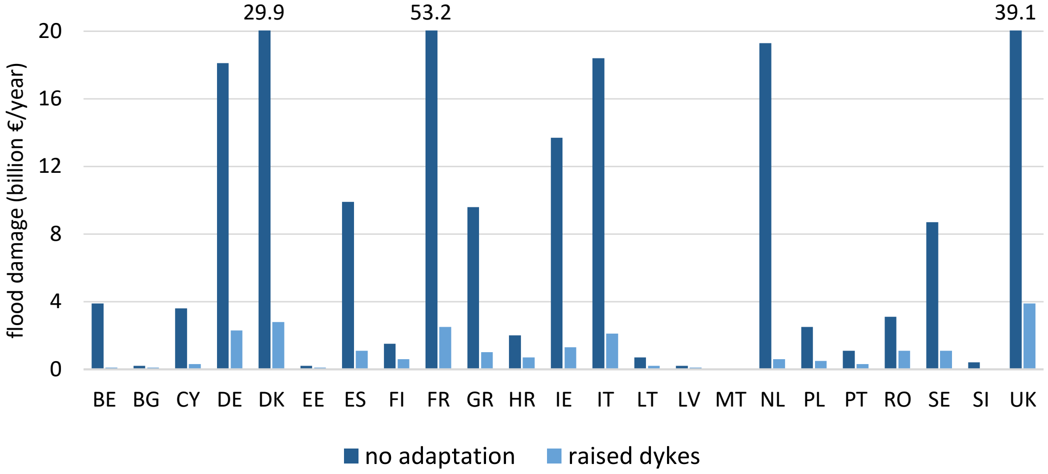


Figure 20. National annual damage without and with adaptation (high emissions by 2100).

Impacts reduction with adaptation

If dykes are raised along EU and UK coastlines, to a level of protection for each section that maximises their economic benefit (avoided flooding) relative to their cost, then annual flood damage could be reduced significantly relative to no adaptation (Figure 19 and Figure 20). Under the high emissions and moderate mitigation scenarios in 2100, the damage is reduced by 90% (216 €billion/year) and 89% (97 €billion/year), respectively. Likewise, 63% (1.3 million/year) and 59% (0.8 million/year) fewer people would be exposed to coastal flooding respectively. The average annual cost of adaptation for the EU and UK over the period 2020-2100 is 1.9 €billion/year in the high emissions scenario and 1.3 €billion/year in the mitigation scenario. The UK, Germany and France have the highest adaptation costs because of higher construction costs and amounts of coastline where additional protection is required. The average annual cost of additional coastal protection is about two orders lower than the estimated reduction in annual flood losses by the end of the century. This means that investing now in coastal protection will have very large (and growing) benefits in the long term.

The costs and benefits of raising dykes varies strongly between coastal segments in Europe. The presence of human settlements makes investing in dykes economically beneficial, typically when population density exceeds 500 people per km^2. In urbanised and economically important areas the benefits of raising dykes tend to be several times the costs, which is the case for 19% and 23% of the European coastline under moderate mitigation and high emissions, respectively. However, for the rest of Europe's coasts, additional protection against coastal inundation is neither needed nor economically beneficial. This can be either because natural barriers will sufficiently safeguard against the projected rise in sea level extremes in areas with steep morphology, or because costs of raising dykes outweigh the benefits, which can happen in sparsely populated areas and along complex, winding coastlines.

The average rise in coastal defence height where further protection is needed in the EU is 100 and 84 cm under a high emissions and moderate mitigation scenario respectively. In Belgium this is even more than two metres, and also in Slovenia, Latvia, Poland, Germany, the Netherlands and the UK additional protection well above one metre will be required. This implies that along many densely populated and economically pivotal coastal stretches of the EU the shoreline may become disconnected from hinterland areas.

Factors that control costs and benefits of raising dykes

The results of the cost and benefit analysis are sensitive to some implementation choices. Shoreline length applies a critical control on the costs of dyke upgrades, which could be reduced substantially in areas with highly fractal coastlines by installing defences further inland. The outcomes are also very sensitive to discounting, which gives more weight to present capital costs and downgrades the benefits that will mostly come later in the century. We used discount rates in line with the EC Guide to Cost-Benefit Analysis of Investment Projects that were assumed constant in time. Using lower or time-declining social discount rates strengthens the case that we should act now to protect future generations. Similarly, dyke heights are optimised here considering the most likely projection of future extreme sea levels. Decision-makers could select a more conservative criterion and aim to protect against the high-end, less probable future extreme sea level scenarios. This would require higher investments but imply less risk for future generations.

Impacts of climate change on coastal zones are not limited to growing coastal flood risk. Coastlines will also be subject to increased potential of erosion, the loss of low-lying coastal ecosystems, and landward intrusion of saltwater, some of which can also be mitigated by raising dykes. Direct damage to port and maritime infrastructure are also not fully captured. In addition, the present assessment is limited to the 21st century, but sea levels and consequent flood risk are expected to continue to rise well beyond 2100, even with accelerated rates. Including these effects would render additional protection as even more economically beneficial.

Approach

Projections of sea level rise, waves, storm surges and tides under a high emissions scenario (RCP8.5) and moderate mitigation scenario (RCP4.5) respectively, were used to estimate extreme sea levels up to the end of this century. These were used to generate flood inundation maps from which population exposure and damage were estimated using depth-damage functions. Future changes in population and economic activities are those from the ECFIN Ageing Report.

The level of adaptation (i.e. height in cm of raising dykes) was determined for each section of coastline by identifying the raised height that maximises the sum over the project lifetime (up to 2100) of the costs and benefits associated with the investment, assuming discount rates of 5% (Cohesion Fund countries) and 3% (other Member States). The costs were calculated as the sum of national-level capital investment costs to raise dykes and maintenance costs. The benefits are the damage avoided by increasing the dyke height, calculated as the difference between future damage with and without raised dykes respectively. Flood losses, costs and benefits are presented undiscounted in general, but in the cost-benefit analysis of adaptation future costs and benefits are discounted. The benefit-cost ratio, which is the ratio of total benefits to total costs, is also based on discounted values and was calculated for each section of national coastline, at NUTS2, country and EU+UK level. More details in Vousdoukas et al. (2020).

10 Wildfire danger and vulnerability

In 2018 more EU countries than ever were hit by wildfires, with Sweden experiencing the worst fire season in reporting history[1]. In the first half year of 2019 the number of fires recorded in the EU was three times the average over the past decade. Changing weather conditions associated with global warming could further increase fire danger in most of Europe. The projected increase in fire danger is strongest in southern European countries, where fires are already frequent and intense. The number of people living near wildland and exposed to high-to-extreme fire danger levels for at least 10 days per year would grow by 15 million (+24%) with 3°C warming, compared to now. Climate change would also result in major shifts in the locations of current ecological domains and induce stress on the structure and composition of vegetation, leading to increased vegetation vulnerability to fires. Mitigation alone is not enough to avoid adverse climate change impacts and adaptation strategies will be needed in order to enhance social–ecological resilience to wildfires.

Wildfires in Europe today

In recent years, large wildfires have repeatedly affected Europe. Mediterranean countries like Portugal, Spain, Italy, Greece and France, are currently most prone to fires and account for around 85% of the total burnt area in Europe. In these countries, fires destroyed nearly half a million hectares per year on average between 1999 and 2016. In 2017, the worst year over the last two decades, the total burnt area in Portugal, Spain, and Italy alone exceeded 0.8 million hectares. In 2018, vulnerable ecosystems of the Natura 2000 network, home to several endangered plant and animal species, lost 50,000 hectares to fires, accounting for approximately one third of the total burnt area.

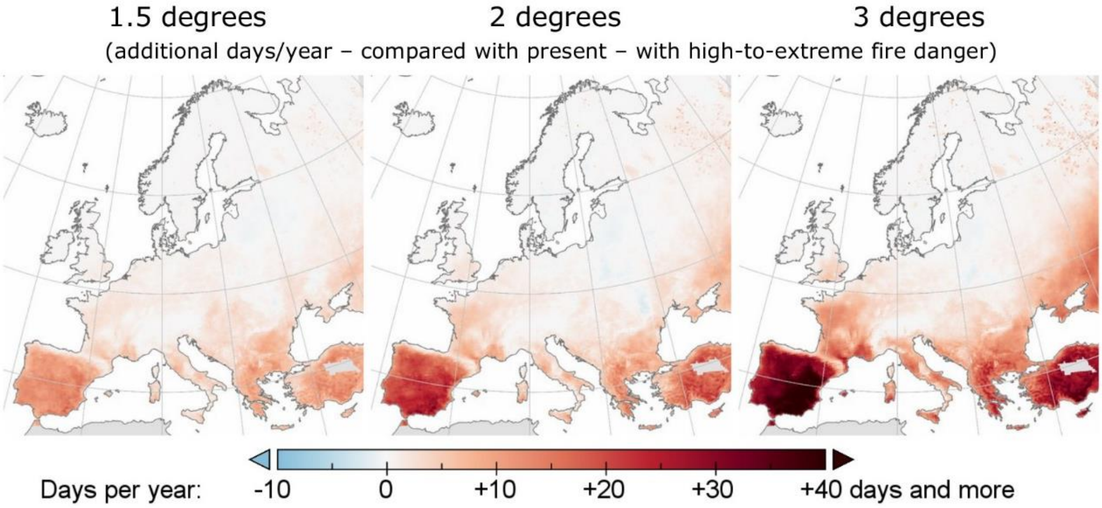


Figure 21. Additional number of days per year with high-to-extreme fire danger (daily Fire Weather Index ≥ 30, see Approach) for different levels of global warming compared to present (1981-2010).

Wildfire danger on the rise with global warming

The number of days per year with high to extreme wildfire danger is projected to rise nearly everywhere in Europe with global warming as a result of higher temperatures and increased spells of dryness (Figure 21). Only in scattered parts of northern Europe (the area around and south of the Baltic Sea) are the number of high to extreme fire danger days projected to decrease slightly. Fire danger will worsen especially in southern regions of Europe that already face high fire danger conditions more often. Although the projected worsening of fire danger is smaller with 1.5°C global warming, relative to 2°C or 3°C warming, fire danger would still be

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[1] San-Miguel-Ayanz, J., Houston-Durrant, T., Boca, R., Libertà, G., Branco, A., de Rigo, D., Ferrari, D., 2019. Forest fires in Europe, Middle East and North Africa 2018. Publications Office of the European Union, Luxembourg.

consistently worse compared to present. This suggests that mitigation alone will not be sufficient to lessen possible impacts of climate change.

Population in Wildland-Urban Interface exposed to fire danger

The number of European[1] citizens living near wildland and exposed to at least 10 days of high-to-extreme fire danger per year is projected to increase from 63 million in the present to 78 million with 3°C global warming, an increase of 15 million people (24%). When global warming is restricted to 1.5°C, an additional 5 million people would be exposed compared to now, or approximately 10 million fewer people compared with no mitigation.

Climate change will exert stress on ecosystems and increase their vulnerability to fires

Global warming could result in a substantial shift northwards of European ecological domains (Figure 22). This results in a substantial contraction of the Boreal domain, as the Temperate domain migrates to the north. The Subtropical domain is projected to expand around the Mediterranean region and to contract in southern parts of the Mediterranean region, where the Tropical domain, currently absent in Europe, is expected to encroach and could become a significant ecological component. The degree of change in ecological domain components increases with the level of warming and could be considerably halted with climate mitigation.

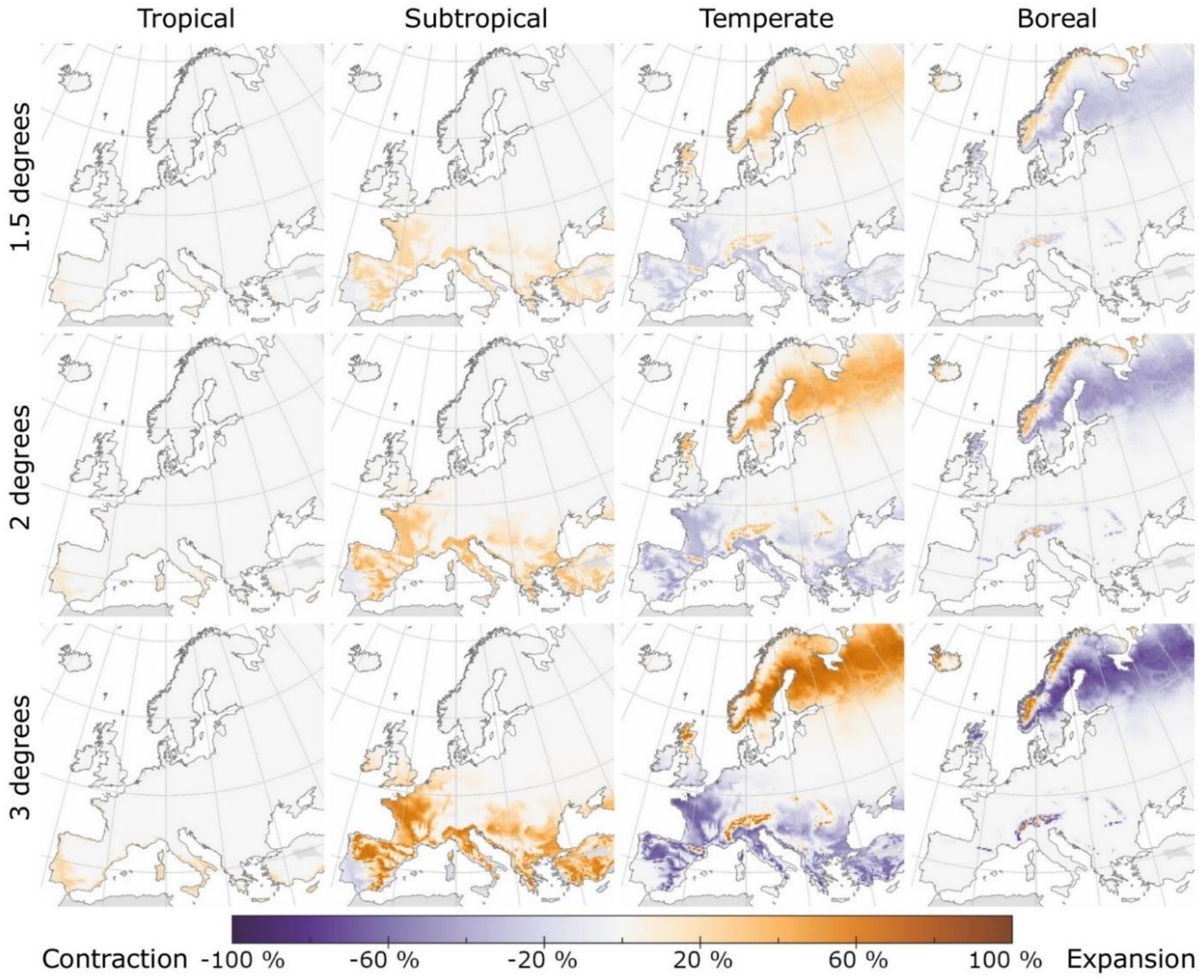

Figure 22. Projected changes in ecological domain components with global warming, relative to present (1981-2010).

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[1] Statistics based on available data for countries in EU, UK and EFTA, candidate countries and potential candidates.

The projected changes (both expansions and contractions) will have a direct influence on the structure and composition of wildland vegetation (forests, shrub and grassland) and corresponding fuel characteristics. This may exert stress on the vegetation and increase their vulnerability to fires, but also affect vegetation recovery after the fire. Recovery could become impossible where the intensity of eco-domain shift would prevent pre-fire ecosystems from re-establishing.

The need for adaptation

The projected increase in fire-conducive climate conditions in many regions of Europe, even under the lower levels of global warming, suggests that various adaptation mechanisms will be needed to lessen the potential effects of wildfires on people and ecosystems. Most fire ignitions in Europe are linked to human actions, including negligence and arson. Awareness campaigns and wildfire prevention programmes could help to reduce the number of human-ignited wildfires. Active forest management practices can also counteract the impacts of a changing climate. For example, fuel reduction management or prescribed burning can limit the build-up of fuels and decrease forest vulnerability. Where feasible and subject to the constraints imposed by ecological domain shifts, changing to less flammable species (e.g. from conifers to deciduous) and recreating mixed forests might be also a viable option in the longer term. Through adequate landscape management, natural fire breaks (e.g. agricultural land) can be created to prevent the spread of fire and reduce the area burned. Finally, increasing awareness on health hazards from smoke plumes from fires in the immediate vicinity and at larger distances could mitigate human impacts, especially for citizens with pre-existing health conditions, and those operating in wildfire emergency response.

Approach

PESETA IV estimated components of wildfire danger and vegetation fuel vulnerability for present climate and for 1.5°C, 2°C and 3°C of global warming above preindustrial levels using an ensemble of bias-corrected climate projections for a high emissions (RCP8.5) scenario and a moderate-mitigation (RCP4.5) scenario.

The Canadian Fire Weather Index (FWI) was used to estimate numerically the weather-driven fire danger using simulations of temperature, wind speed, relative humidity and precipitation. The FWI rates fire intensity by integrating the effects of fuel moisture and wind on fire behaviour. It was calculated at high spatial resolution and at a daily time step, taking into account weather conditions in preceding days. The daily fire danger estimates were grouped in classes of fire danger from days with low danger up to days with extreme danger. Values of FWI above 20 are associated with high fire danger, while values exceeding 50 typically characterise extreme danger conditions. The probability of occurrence of each class was calculated as the number of days per year that the FWI falls within the range of the respective class. The number of people living in the vulnerable interface between wildland and settlements (Wildland-Urban Interface) was assessed at high-resolution by combining land use information and population density maps.

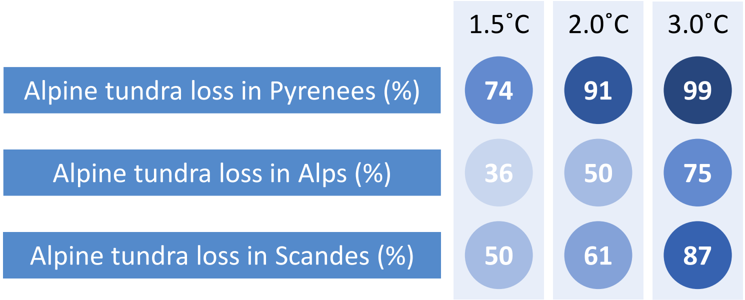
Potential shifts of ecological domains due to global warming are an indication of future vegetation vulnerability to fire. Changes in the spatial distribution of tropical, subtropical, temperate and Boreal ecological domains (following the global definition of the UN Food and Agriculture Organization) and local ecological patterns were assessed based on the temperature projections. More details in Costa et al. (2020).

11 Alpine tundra habitat loss

The alpine tundra domain occurs at altitude in the high mountains in Europe. It is an important reservoir of freshwater and provides habitat to unique species. The treeline, which is below the domain, represents the forest limit. About 98% of Europe's alpine tundra domain is in the Pyrenees, Alps and Scandes. In a 3°C warming scenario, the natural climatic treeline is projected to move vertically upwards by up to 8 metres per year and over Europe the domain could shrink by 84% of its present size. In the Pyrenees high warming could lead to a near total loss of the alpine tundra. Limiting warming to 1.5°C could reduce the loss of alpine tundra to 48%. The projected changes have implications for vital ecosystem services, habitat for biodiversity, and recreational services such as skiing. Adaptation is challenging because of the unique topographic, soil and climatic characteristics of high mountain systems.

Shrinkage of the alpine tundra domain

Alpine tundra currently covers around 87,000 km^2 in Europe, of which around 25,000 km^2 in the Alps, 1,800 km^2 in the Pyrenees and 59,000 km^2 in the Scandes. This is close to the size of Austria or Portugal. However, the domain is projected to shrink significantly with global warming (Figure 23). There are large differences in the losses projected for the three main regions that make up the domain: the most severe impact is projected for the Pyrenees, where the current domain virtually disappears with 3°C, compared to the Scandes and Alps, which would shrink by around 87% and 75% respectively. The magnitude of loss is smaller at lower warming levels but it is still significant: with 1.5°C global warming the alpine tundra domain in the Pyrenees, Scandes and Alps reduces in area by around 74%, 50% and 36% respectively (Figure 23).

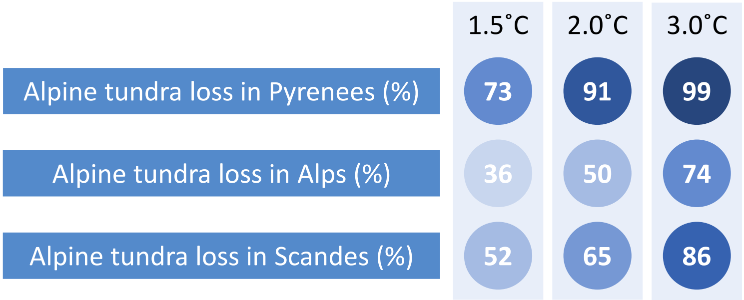


	1.5˚C	2.0˚C	3.0˚C
Alpine tundra loss in Pyrenees (%)	74	91	99
Alpine tundra loss in Alps (%)	36	50	75
Alpine tundra loss in Scandes (%)	50	61	87

Figure 23. Projected shrinkage of alpine tundra (%) compared to present.

Losses of alpine tundra in Natura 2000 sites

Over 16,000 km^2 of current alpine tundra domain are Natura 2000 sites, a network of nature protection sites established under the EU Habitats Directive, approximately 20% of the total extent of the current alpine tundra domain. Of the 210 sites that contain alpine tundra, almost all of them are projected to see a shrinking of the domain: 207 and 208 in the 2°C and 3°C warming scenarios respectively. The magnitude of shrinkage is already significant under the 1.5°C warming scenario: the current domain within Natura 2000 sites shrinks by between 36% (Alps) and 73% (Pyrenees; Figure 24). The contraction increases gradually with warming, and in the 3°C warming scenario the current domain inside Natura 2000 sites shrinks by over 74% in all three of the mountain regions where most of Europe's alpine tundra is currently found. With unmitigated climate change practically all alpine tundra Natura 2000 sites in the Pyrenees could be lost.



	1.5˚C	2.0˚C	3.0˚C
Alpine tundra loss in Pyrenees (%)	73	91	99
Alpine tundra loss in Alps (%)	36	50	74
Alpine tundra loss in Scandes (%)	52	65	86

Figure 24. Projected shrinkage of alpine tundra within Natura 2000 sites (%) compared to present.

Vertical shifts in the treeline

The natural climatic treeline is projected to gradually advance vertically upward in mountain regions of Europe with global warming (Figure 25). The rate of treeline shift generally increases at lower latitudes, where climatic treelines are already higher. In the southernmost mountain regions the treeline moves upwards by around 6-7 m every year in the 1.5°C warming scenario, compared to 2-3 m/year at high latitudes. In a 3°C warming scenario, the treeline in the Pyrenees could reach 2,317 m compared to 1,675 m now (+642 m). In the Alps, the treeline could shift from 1,762 m at present to 2,288 m (+526 m) with 3°C warming, while in the Scandes it could climb from 523 m to 859 m (+336 m).

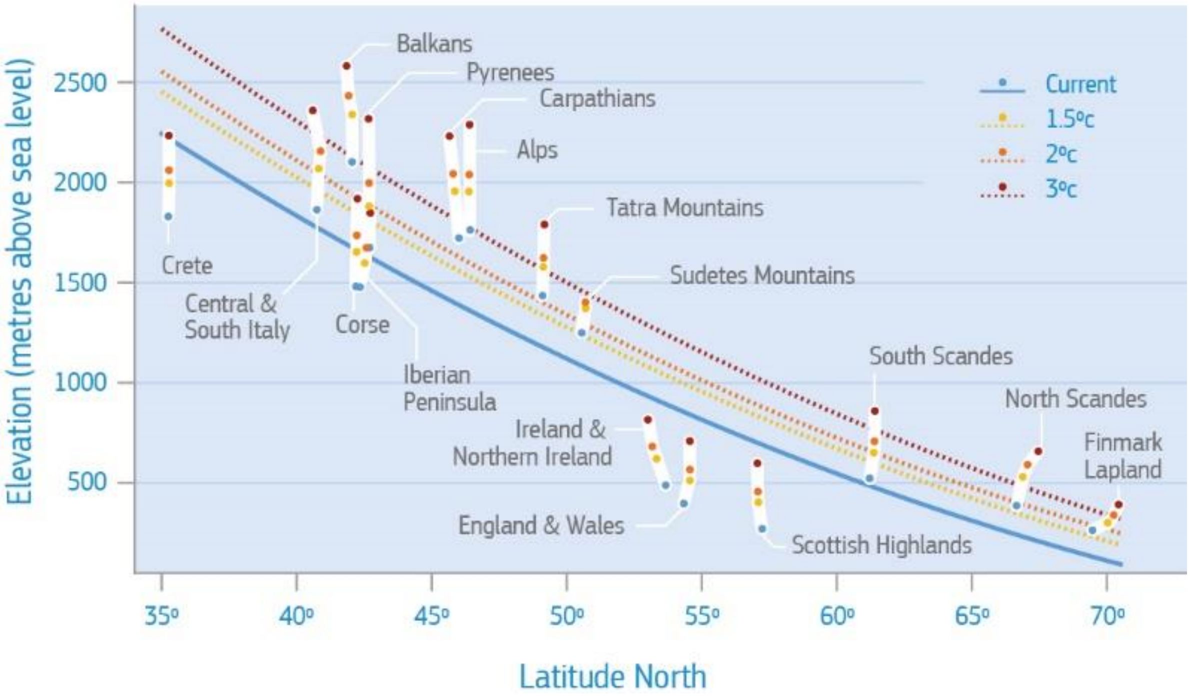


Figure 25. Climatic treeline elevation for 16 mountain regions in Europe, currently, and in 1.5°C, 2°C and 3°C warming scenarios. White lines group impacts for each region. Solid and dotted lines show best regression fit for each scenario.

Implications and need for adaptation

Snow retains water above the treeline that is released during the summer months. Shrinkage of the alpine tundra domain could alter available water resources downstream in summer months. It is also associated with a shrinkage of alpine glaciers, causing debris flows and reductions in water quality due to an increase in the amount of sediments in rivers. Cold mountain habitats would decline, leading to local extinction of some alpine plant species. Warm-adapted species would increase at the expense of declining cold-adapted species. Shrinkage of the alpine tundra domain would likely restrict winter sports.

Ecosystem-based adaptation options include ecological restoration, increasing biological diversity, assisted migration of threatened species, ecological corridors, ex-situ conservation and seed banks. Several of these options face constraints arising from the unique topographic, soil and climatic characteristics of alpine tundra regions. Migration of species could be constrained by the lack of sufficient altitude to migrate vertically or due to limiting soil conditions for plant growth. The feasibility of the implementation of adaptation measures should therefore be assessed at local level. Potential trade-offs between adaptation for nature conservation and adaptation for winter tourism should also be considered.

Approach

PESETA IV assessed the effects of climate change on the spatial range of the alpine tundra zone in the high mountain ranges of the Pyrenees, Alps and Scandes. Climate projections under a high emissions scenario (RCP8.5) and moderate mitigation scenario (RCP4.5) were used in order to delineate the alpine tundra domain for baseline (1981-2010) climate and at global warming of 1.5°C, 2°C and 3°C above preindustrial levels. Alpine tundra was mapped using a climate classification equivalent to polar climates, where the mean temperature of the warmest month is less than 10°C. The projections of temperature were corrected for bias and downscaled to high spatial resolution accounting for altitude effects. Projected changes in the alpine tundra domain were then classified in three potential categories: stable, contraction and expansion. Natura 2000 sites projected to be affected by changes of the alpine tundra were identified by overlying areas that are projected to remain stable, contract or expand with the map of Natura 2000 sites.

Treeline shifts with global warming are assessed in 16 mountain regions in Europe, from the Mediterranean islands to the Boreal and from the Iberian Peninsula to the Carpathians, including the more prominent treeline ecotones of Europe. The treeline position was mapped based on a growing season canopy temperature threshold of 7.6°C. The impacts of declines in the alpine tundra domain and vertical shifts in the treeline, as well as potential adaptation options, were considered by reviewing the available literature – it was not modelled specifically by PESETA IV. More details in Barredo et al. (2020).

12 Forest ecosystems vulnerability

Forests cover around one third of the land surface in Europe. They provide key ecosystem services that contribute to human well-being and climate mitigation. Forests are vulnerable systems because the long life-span of trees limits rapid adaptation to drastic environmental changes. In recent years, about 14 billion tonnes of above ground forest biomass in the EU, or two third of total stand biomass, was found to be potentially vulnerable to natural disturbances. Hotspot regions with forests susceptible to windthrows, fires and insect outbreaks are located in both southern and northern Europe. This spatial pattern is strongly controlled by the interplay of forest characteristics with the background climate. The combination of rising temperature and changes in precipitation in the last two decades have likely reduced plant defence mechanisms and increased their vulnerability to insect outbreak disturbances, especially in high-latitude regions. Global warming will likely increase natural disturbances in the future, especially those from fires and insect outbreaks that are more severely affected by climate.

Forest vulnerability across Europe

At present around 26 billion tonnes of forest biomass in Europe is potentially vulnerable to natural disturbances. Nearly half of that amount (46%) is threatened by windthrows, followed by forest fires (29%) and insect outbreaks (25%). There is substantial spatial variation across Europe in the vulnerability of forests to the different natural disturbances (Figure 26). Vulnerability to windthrows is higher in northern Europe, prominently in Norway, the British Isles, and in southern Europe. In these regions, up to 60% of the stand biomass is potentially vulnerable in areas affected by windthrows. A prominent south-north gradient of increasing vulnerability to fires and insect outbreaks emerges, with peak values in northern Europe, particularly in the Scandinavian Peninsula, and European Russia where areas affected by these disturbances may lose up to 30% of stand biomass.

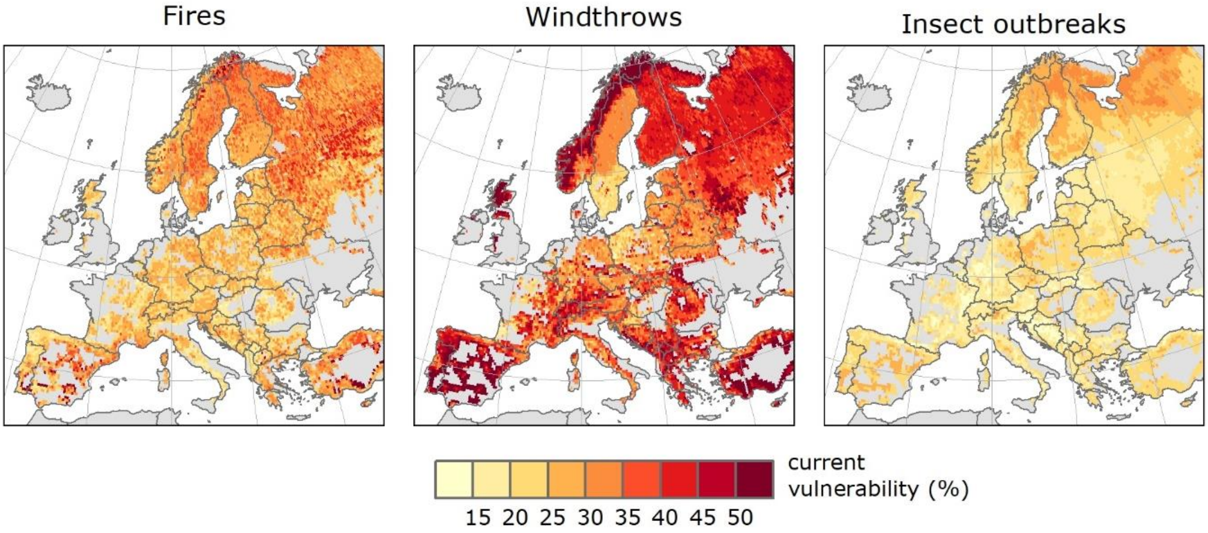


Figure 26. Forest vulnerability to major natural disturbances in Europe, expressed as the share (in %) of biomass that would be lost in case of a disturbance. Areas with forest cover fraction lower than 10% are masked out (in grey).

Drivers of forest vulnerability

Forest characteristics, notably above ground biomass, growing stock volume, leaf area index, tree age and tree density, largely control forest vulnerability to fires and windstorms. For these disturbances, forest structural characteristics have more important effects than climate and landscape conditions over most of Europe (**Figure *27***. Contribution of forest, climate and landscape characteristics to forest vulnerability for three major disturbance types.Figure 27), although climate features can exert a strong control on fire disturbance in parts of northern Europe and on windthrow disturbance in eastern Russia. For insect outbreaks, climate conditions play a more prominent role. In particular, anomalies in precipitation and temperature are key drivers of forest vulnerability to insects in most of northern Europe, alpine regions and European Russia, while forest characteristics are critically important in most forests of central and southern regions of Europe. Overall, landscape features overall have a minor effect on vulnerability to natural disturbances, with slightly larger effects on fires in European Russia and on insect outbreaks in eastern Europe.

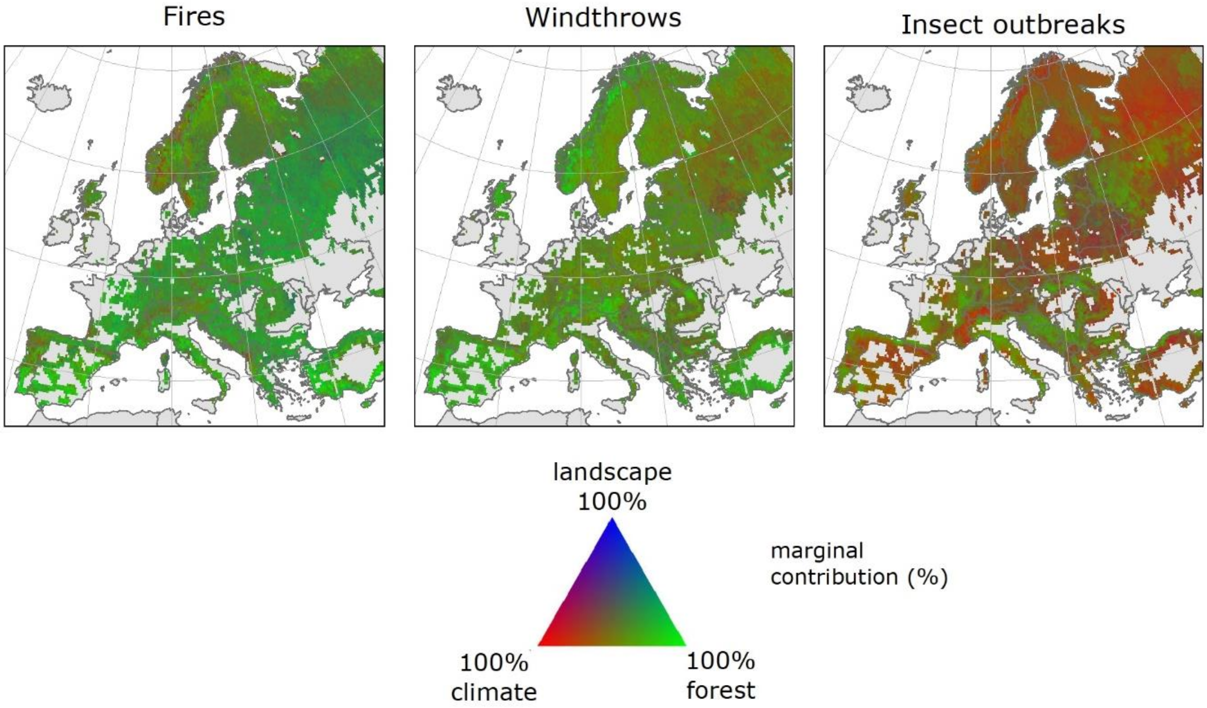


Figure 27. Contribution of forest, climate and landscape characteristics to forest vulnerability for three major disturbance types.

Trends in forest vulnerability

Over the last two decades, an increasing amount of forests in Europe has become vulnerable to insect outbreaks, particularly in high-latitude areas, showing regional trends that can exceed 0.12 tonnes per square hectare per year. No clear trends can be detected in the forest vulnerability to windthrows and fires over this period. In fact, the temporal variations in vulnerability to fire and wind disturbances show a mixed spatial pattern. When aggregating over Europe and the different disturbances, a clear increasing trend in biomass vulnerability emerges for the recent years with a change of about 0.04 tonnes per square hectare per year.

The wind analysis of PESETA IV shows no clear trend in extreme wind speeds with global warming while the forest fire analysis of PESETA IV projects a climate-driven increase in fire danger in most of Europe, especially in southern regions. Rising temperatures and more spells of dryness with global warming, especially in southern Europe, could lead to increasing biomass loss from insect outbreaks and fires. It is therefore likely that with increasing levels of global warming, forest disturbances are more likely to occur.

Approach

The vulnerability of European forests to three major natural disturbances was assessed: fires, windstorms and insect outbreaks (bark beetles, defoliators and sucking insects). Vulnerability is expressed here as the degree to which forest ecosystems are affected when exposed to a disturbance and it is quantified in relative biomass loss. Such estimates should, therefore, not be confounded with risk levels, as they do not integrate information on the probability of occurrence of disturbances (hazard). For each disturbance type, a machine learning model was derived to predict biomass loss of plant functional types based on a number of forest, climate and landscape parameters. Forest characteristics include vegetation parameters describing the forest state and productivity, such as biomass, growing stock volume, leaf area index, tree age, tree density and tree diameter. Climate information includes long term averages of temperature and precipitation and anomalies therein in the years preceding the disturbance, as well as extremes of wind and aridity in the year of the disturbance. Landscape features include population density, spatial vegetation variability metrics and geomorphological parameters. The vulnerability models are calibrated and validated using a large set of records of forest areas affected by natural disturbances over the period 2000-2017. The vulnerability models were then used to extrapolate in space and time the annual vulnerability of forest. Based on the resulting time series, spatial patterns and temporal variations in vulnerability were evaluated. More details in Forzieri et al. (2020).

13 Impacts on agriculture

Extreme dry and hot weather spells in recent years have cut agricultural output in important crop regions in Europe and around the world. In order to understand how the agriculture sector in the EU could be affected by climate change, PESETA IV conducted an integrated quantitative assessment, involving climate, biophysical and economic models. In the absence of adaptation, climate change is expected to substantially lower grain maize and wheat yields in southern Europe, and to a lesser extent grain maize yields in northern Europe. However, EU production could still slightly increase due to the interplay of different market forces. This is because the negative effects in Europe are projected to be lower compared to the other world regions. This provides the EU a comparative advantage in terms of climate change impacts on agricultural productivity, which could positively affect its competitiveness.

Climate change driven biophysical impacts in Europe

Grain maize is an irrigated crop in most of Europe. When assuming that the irrigation infrastructure of nowadays remains in place and that sufficient water is available for irrigation (i.e. projecting “potential yields”; top panels in Figure 28), climate change will substantially lower yields in most producing EU countries. The most severe impacts on irrigated grain maize are projected for southern Europe, where potential yields could decline by more than 10% in a 2°C warming scenario. The losses are slightly lower with 1.5°C warming.

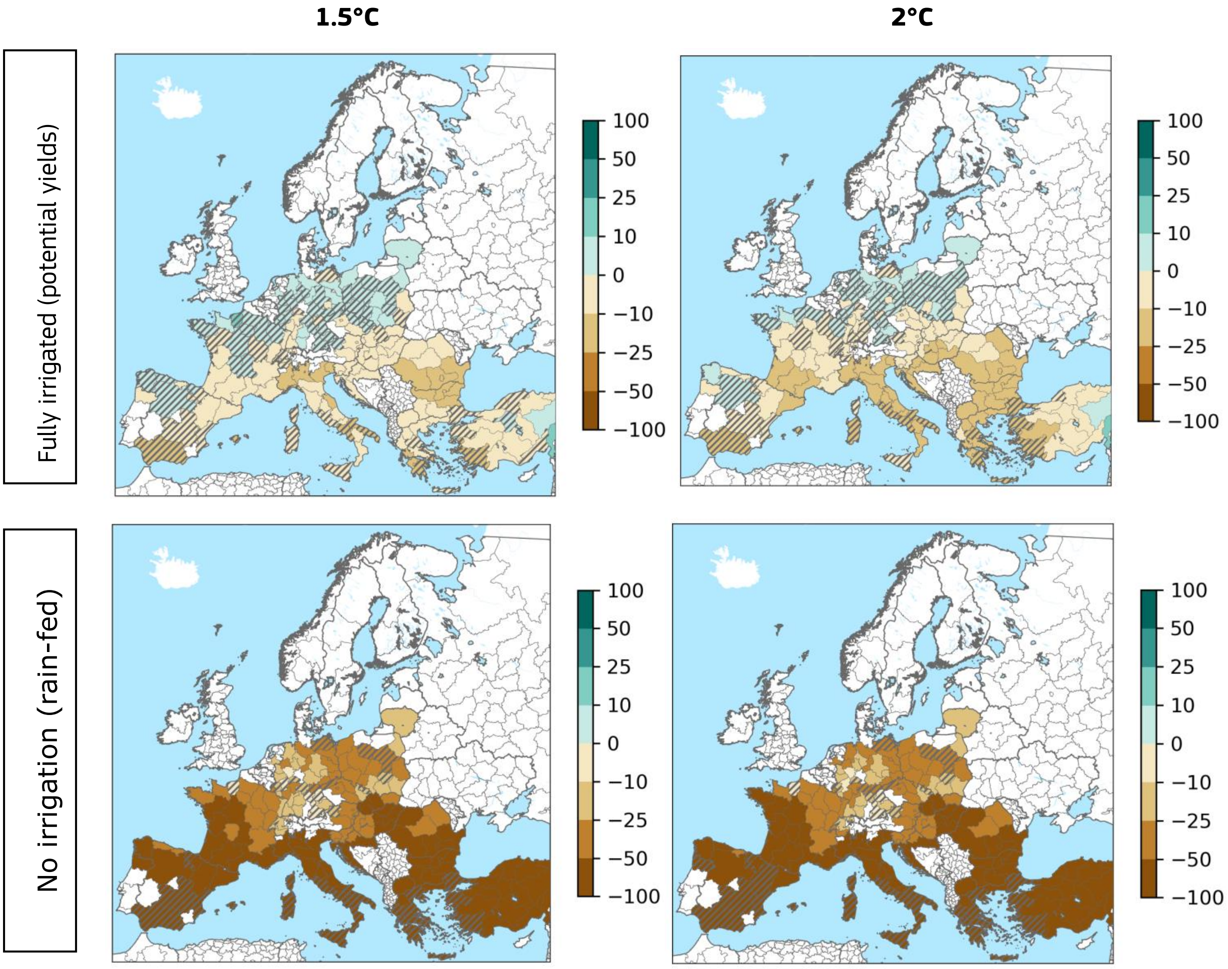


Figure 28. Results of the biophysical assessment, showing ensemble mean changes of grain maize yield relative to baseline (%) for 1.5°C (left panels) and 2°C (right panels) warming scenarios, assuming fully irrigated conditions (“potential yields”; top panels) or no irrigation in the future (“rain-fed yields”; bottom panels). Hatching denotes areas with low agreement in model responses to global warming.

Climate change could further restrict the water available for irrigation and result in yields that are lower than the potential achievable under full irrigation. Under the extreme assumption of no irrigation in the future, severe declines in grain maize yield are projected with global warming (Figure 28, bottom panels). Under such “rain-fed” conditions, declines in yield of over 20% are projected for all EU countries, with crop losses up to 80% for some countries in southern Europe (Portugal, Bulgaria, Greece and Spain). This implies that without market adjustments, grain maize production may no longer be viable in areas where there is water scarcity and precipitation significantly decreases.

In contrast to grain maize, wheat is mostly a non-irrigated, rain-fed crop in Europe. Increases in yields by around 5% on average are projected for northern Europe, due to changes in precipitation regime combined with an anticipated growing cycle and enhanced growth from increasing atmospheric CO_2 concentrations. Yield reductions are projected for southern Europe by 12% on average, corroborating empirical evidence of a limited CO_2 effect on wheat under limited water conditions. Limiting global warming to 1.5°C could reduce these losses by 5%.

Adaptation in Europe

Adaptation strategies, such as changing sowing dates and the crop variety sown, would not suffice to offset the projected strong reduction in grain maize yields. Changing varieties could have a much larger beneficial effect on rain-fed wheat production. Plant-breeding, guided by modelling, can identify ‘faster’ wheat varieties, which reach the flowering stage earlier. These may lessen the projected yield reduction from climate change and in some cases even give rise to an increase in yields. Furthermore, if irrigation infrastructure is built in wheat growing areas and assuming there is sufficient water availability, wheat losses could turn into yield gains across all of Europe. As climate change progresses, farmers may also decide to grow different crops, which are more suited for the new agro-climatic conditions.

Crop production impacts with market adjustments

The negative effects of climate change on crop yields in the EU as projected by the biophysical models may be reduced considerably as a result of market adjustments due to more severe climate change impacts on agriculture outside Europe. The differently projected biophysical yield changes across regions will result in changes in global production, reflected in positive changes in crop prices. Due to market adjustment effects, the price increases will induce changes in EU farmers' management practices (e.g. input use per unit of land) which in the end makes yields readjust. For example, with market adjustments, in southern Europe there is a 3% increase in grain maize and a 2% increase in wheat production (Figure 29), which is different than the projected declines for both crops in the biophysical assessment (Figure 28). In northern Europe, however, the substantial increase in wheat yield projected by the biophysical assessment is downsized due to market adjustment.

Besides the market adjustment effect, there are other methodological limitations that need to be highlighted and are responsible for the differences in the biophysical and economic projections. More specifically, the use of different climate and crop models, slightly varying magnitudes of global warming, as well as different modelling assumptions around irrigated and rain-fed yields, effect of elevated atmospheric CO2 concentration, changes in crop varieties and sowing dates are also responsible for the projected differences between the two approaches.

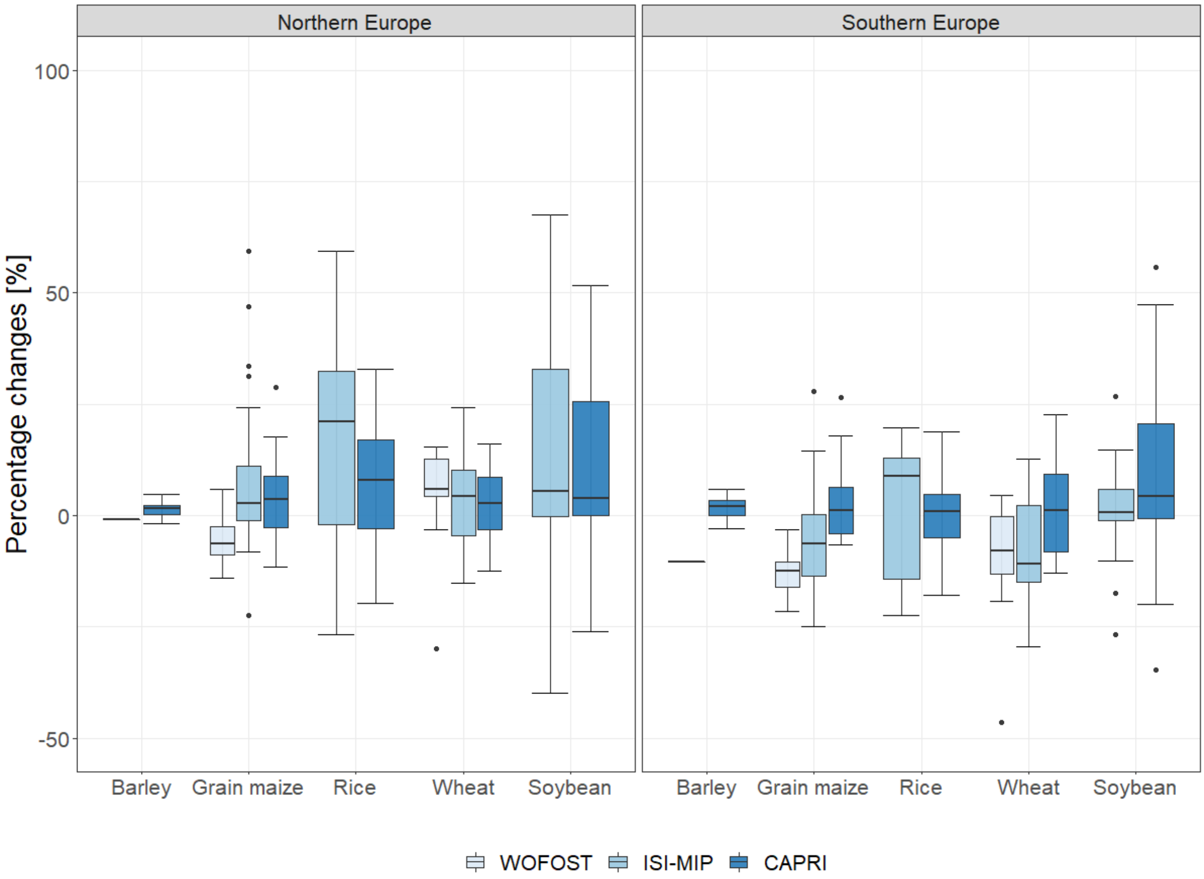


Figure 29. Crop yield changes (%) for northern and southern Europe in 2050 relative to the baseline based on biophysical modelling (WOFOST, ISI-MIP) and economic modelling (CAPRI) when accounting for market adjustments. Horizontal lines show the ensemble median and boxes show the 25th and 75th percentiles. The warming in this scenario in 2050 corresponds to approximately 2°C.

Approach

The WOFOST model was used in the biophysical assessment to simulate crop yields across Europe under 1.5°C and 2°C warming scenarios derived from 10 regional climate models run for two emission pathways (RCP8.5 and RCP4.5). Crop growth was affected by elevated CO_2 concentrations. Two types of yields were estimated: 1) "potential yields", where it was assumed that current irrigation infrastructure remains in place in the future and there is sufficient water available for irrigation; and 2) "rain-fed yields", where there is no irrigation and therefore crops can be affected by water availability constraints. The effects of respectively including and excluding adaptation options such as changing sowing dates and crop varieties were explored. The effects of nutrient limitations, heat stress at flowering, and pests and diseases were not considered.

The CAPRI model[1] was used to explore the effects of global climate change on European crop production, land use, consumption, income, prices and trade. Yields for year 2050 from 7 global crops models, run with five global climate models under the RCP8.5 emissions scenario (source: ISIMIP Fast Track database), were used as input to CAPRI. WOFOST could not provide climate change yield changes for the rest of world and was therefore not added to the model ensembles. For Europe, there is a partial overlap between the ISIMIP and WOFOST crop yield projections. The range in global warming across the climate models in 2050 is 1.6-2.7°C. CAPRI did not consider water availability constraints, the effect of elevated atmospheric CO_2 concentrations, nor changes in crop varieties and sowing dates. More details in Hristov et al. (2020).

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[1] www.capri-model.org

14 Impacts on electricity production

PESETA IV assessed the impacts of climate change on electricity production by hydro, wind, solar, nuclear and other thermal power plants, including biomass, coal, gas and oil. We assessed how climate change would affect the present power system (static scenario) and the power system of 2050 in line with 2°C mitigation efforts (dynamic scenario). Under both scenarios, at EU-level hydropower increases with global warming while nuclear power decreases. However, there are regional differences in the impacts, such as increased hydropower in the north, and a decline in hydro and nuclear power in southern Europe due to lower water availability for direct production and cooling river-based plants. In northern Europe, the increasing availability of cheaper hydro results in substitution effects and lower production costs, while in southern Europe production costs could increase. The direct impacts of climate change on wind and solar production are not significant. However, in the 2050 power system their capacity would increase in southern regions to compensate for the lost hydro and nuclear production. Climate change impacts on energy in the rest of the world show a negligible spill-over effect on Europe. Improved cooling technologies have the potential to strongly reduce the negative effects of water scarcity, particularly for nuclear plants in southern Europe.

Impacts on electricity production

Global warming results in an overall increase in hydropower production in the EU + UK, especially in northern regions that rely heavily on hydropower. On the contrary, nuclear power reduces significantly, while other energy sources are only moderately impacted (see Figure 30).

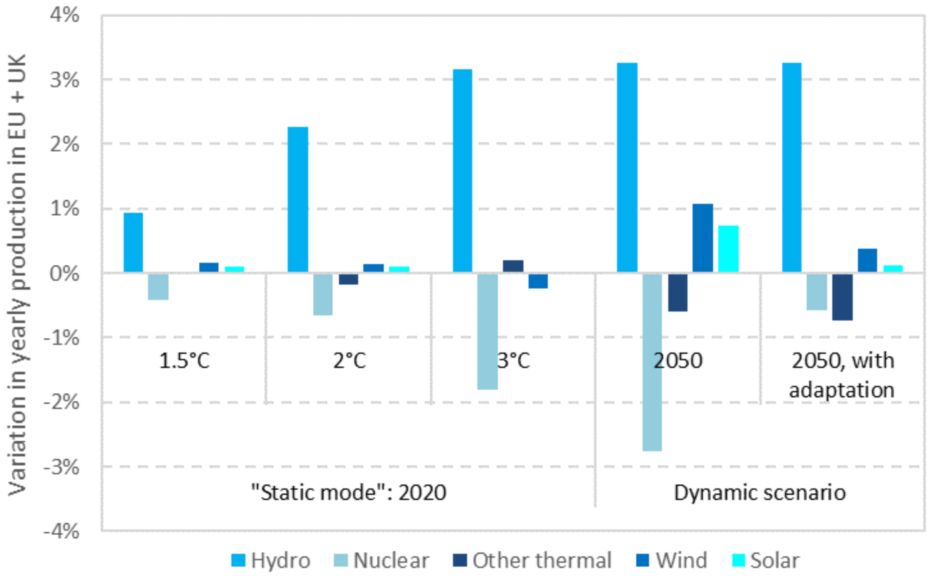

Figure 30. Climate change impacts on power production in Europe (median values of climate ensembles). Impacts of 1.5°C, 2°C and 3°C global warming imposed on today's power system (static scenario), and impacts of 2°C warming on the 2050 power system in line with a 2°C mitigation scenario (dynamic scenario), with and without adaptation of water cooling. Note: "other thermal" designates biomass, coal, gas and oil plants.

When assuming a static 2020 power system, hydropower production in the EU is expected to increase by 0.9% with 1.5°C global warming (median value) and by 2.3% and 3.2% with 2°C and 3°C warming, respectively. Nuclear production would decrease by 0.5% with 1.5°C warming and by 1.8% in a 3°C warming static scenario. Other thermal, wind and solar plants are barely impacted in the 2020 static study and at EU level.

The dynamic scenario includes changes in the energy mix in line with a 2°C climate mitigation scenario (see Approach). The corresponding 2050 power system will also be impacted by climate change. When comparing results in 2050 with and without climate impacts, hydropower production increases by 3.3%, pushing out nuclear (-2.8%) and other thermal production (-0.6%). Wind and solar would develop more (+1.1% for wind and +0.7% for solar aggregated over EU + UK), mainly in response to lower hydro and nuclear power production in southern Europe. The evolution of the mix is in itself an adaptation of the energy system to climate change.

The overall increase in hydropower is dominated by increasing water availability in northern European countries where there is a high installed capacity for hydropower. Since hydro has a lower marginal cost, it undercuts the demand in these regions for power from other energy sources. Depending on the local electricity production mix, the substitution effect is different. In the static scenario, hydro mainly replaces biomass in Sweden, coal in Finland, oil in Lithuania and gas in Latvia. This leads to annual economic benefits in northern Europe of around 1.3 €billion (2015 values) with 3°C warming.

In southern regions of Europe, and particularly the Iberian Peninsula, the projected reduction in water availability negatively affects hydro and nuclear production, especially in summer. Thermal plants act as a substitute to hydro and nuclear in the Iberian Peninsula: in order to ensure demand in periods of reduced hydro and nuclear power, the thermal power capacities in reserve have to increase production. This is more expensive than hydro and nuclear power generation, which means that production costs in southern Europe increase by around 0.9 €billion per year (2015 values) with 3°C warming assuming a static 2020 power system. In the dynamic scenarios, this effect is less pronounced because the increased development of wind and solar contributes to filling the gap left by hydro and nuclear.

In other regions of Europe, changes in water availability are less pronounced, with smaller effects on water-related energy production. As wind and solar are not strongly impacted directly by climate change, the expected impacts on power production in these regions is limited.

Adaptation

In the dynamic scenario, the 2050 energy mix in line with 2°C climate mitigation will further evolve in response to climate change impacts (e.g. increased wind and solar installations). When allowing adaptation of nuclear and other thermal plants, the mix evolution would be different. Nuclear production is particularly reactive and climate change impacts could be almost completely avoided with a switch to less water-intensive cooling technologies (reduction of -0.6% instead of -2.8%, see Figure 30), especially in southern parts of Europe. Other thermal plants do not show a similar benefit of these adaptation measures, either because they do not operate at full capacity or because they are already using efficient cooling technologies.

Spill-over effects

The spill-over effects from the rest of the world on the EU were also quantified (in “static mode”) and appear negligible (less than 0.1%). The main impact at global level is a decrease in fuel consumption and fuel prices because of lower heating demand in buildings. Lower fuel prices could potentially create a slight increase of demand in Europe, which would be covered by reserve capacities of thermal plants as well as some additional decentralised solar capacities.

Implications

Results of this study suggest that energy policies should consider climate change impacts in their electricity production capacity planning. With global warming, hydropower plants will become even more valuable assets in central and northern Europe thanks to increased water availability in these regions. On the other hand, in the south of Europe (especially the Iberian Peninsula and Greece), reduced water availability will reduce the available capacity of hydropower as well as nuclear and thermal plants. Adaptation, through the upgrade to less water-intensive cooling technologies, could avoid most of the loss in capacity, especially for nuclear plants currently based on once-through river cooling. In northern Europe, nuclear and thermal production could decrease due to an increase in hydropower production that has a lower production cost. Finally, wind and solar do not appear to be constrained directly by climate change and could benefit from the negative effects on other technologies, especially in southern regions during summer periods. Expanding inter-regional electricity interconnections is a way to balance the evolving production patterns across Europe and their associated costs. For example, with 2°C global warming, electricity production costs could decrease by 2.5% in northern Europe and increase by 0.6% in southern Europe as a consequence of the changes in water resources and hydropower production, if no additional power trade occurs.

Limitations

The energy supply assessment does not incorporate the effects of climate extremes due to the temporal (seasonal) and spatial (country) resolution of the energy analysis. The drought analysis in PESETA IV shows that increasing drought conditions with global warming in southern and western regions of Europe will result in growing economic losses in the energy sector. Further, increased river and coastal flooding could result in higher direct damage to energy infrastructures in flood-prone areas.

This study assumes that hydropower plants in the EU are not saturated most of the year and that they can benefit linearly from increasing water resources. Similarly, the average wind speeds used here impact linearly wind power production. Although a single turbine has a typical (non-linear) power curve, the relation is more difficult to characterize once the plants of a country are aggregated. The temperature effect on solar PV panels does not reflect the (non-linear) heat accumulation effect, which could result in higher efficiency losses than when considering the ambient temperature. Finally, the water temperature estimation is based on a linear relation with air temperature and lacks a more detailed spatial and temporal modelling.

Approach

PESETA IV estimates the effects of climate change on electricity production by hydro, wind, solar, nuclear and other thermal power plants (biomass, coal, gas and oil). Extreme events such as floods, droughts or windstorms can lead to a temporal disruption of electricity production, transmission or demand. Impacts of drought on energy production have been quantified in the drought analysis of PESETA IV. However, the required temporal and geographical detail is not compatible with the long-term system-wide analysis performed here with the energy model POLES (Prospective Outlook on Long-term Energy Systems). Climate change projections (RCP4.5 and RCP8.5 pathways) and hydrological simulations are identical to those used in the PESETA IV tasks on water resources, droughts and river floods. The impacts assessed relate to changes in water resources availability for hydropower and cooling nuclear and other thermal plants, changes in wind resources for wind energy, and changes in temperature for the efficiency of solar panels. Results are obtained by comparing scenarios with and without the climate impacts on electricity production, so that other factors are neutralized (e.g. climate impacts on energy demand are modelled but not shown here).

A number of different scenarios have been considered. A first analysis looks at the impacts of 1.5°C, 2°C and 3°C global warming on the 2020 power system (energy model used in “static mode”), in order to neutralize other effects such as climate policy or natural power mix evolution. In this “static mode” we further quantified spill-over effects on the EU caused by climate change impacts on energy production in the rest of the world. The energy model was also run in dynamic mode until 2050 corresponding to 2°C compatible mitigation efforts and emission pathway (RCP4.5, with stabilized radiative forcing of 4.5 Watts per square metre in 2100, without ever exceeding that value) and a changing technical and socioeconomic context according to the ECFIN Ageing Report. In this dynamic setting we also quantified the potential of open recirculating cooling (evaporating towers) and dry cooling to reduce the negative effects of climate change on thermal plants cooling. More details in Després and Adamovic (2020).

15 Economic analysis

Climate change damages the capital stock and affects economic production and the welfare of households. For seven climate impact categories these economic effects have been quantified: river floods, coastal floods, agriculture, energy supply, droughts, windstorms and human mortality. Due to the limited coverage of climate impacts, the assessment does not evaluate the full economic impacts of climate change in the EU. Human mortality from extreme heat dominates the economic climate impacts, but its contribution is strongly dependent on the monetary valuation of human life. Welfare losses in southern regions of Europe are estimated to be several times larger compared to those in the north. Limiting warming to 2°C would halve economic impacts compared to a 3°C scenario, while achieving the stringent Paris target of 1.5°C would lower welfare loss by 75%.

Quantifying economic impacts of climate change

The economic analysis was done for seven impact categories: river floods, coastal floods, agriculture, energy supply, droughts, windstorms and human mortality from extreme heat and cold. It is very important to stress that the economic assessment of climate impacts is incomplete: the four other climate impacts categories of the PESETA IV project were not considered because these impacts could not be monetized (e.g., loss of alpine tundra, shift in ecological domains). There are other relevant climate impacts whose economic valuation is not possible given the current state-of-the-art. That is for example the case for effects associated with crossing climate tipping points, ecosystems degradation and loss of habitats and species. Therefore, the integrated economic impacts presented here do not constitute the totality of economic impacts of climate change in Europe and the UK.

The economic analysis was made with a general equilibrium model in a comparative static context, in which we evaluated how different levels of global warming would affect the economy as of today. Hence the results estimated address the question: "How would the current economy be affected if 1.5°C, 2°C and 3°C of global warming would occur today?" This method avoids making assumptions about demographic trends and the future structure and size of the economy and allows to report results that are due to climate change only.

Economic impacts of the damages considered

Exposing present economy to global warming of 3°C would result in an annual welfare loss of at least 175 €billion (1.38% of GDP) for the seven impact categories considered in PESETA IV (Figure 31). Under a 2°C scenario the welfare loss would be 83 €billion/year (0.65% of GDP), while restricting warming to 1.5°C would reduce welfare loss to 42 €billion/year (0.33% of GDP).

The estimated welfare loss with 2°C global warming is very similar to that in PESETA III, which also covered labour productivity and energy demand but not drought and energy supply. PESETA III further estimated a welfare loss of 1.92% of GDP for a high warming scenario of 4°C. Findings of PESETA III and IV therefore corroborate that welfare loss in the EU increases with the level of global warming.

Sectoral impacts

Human mortality from extreme heat dominates the (incomplete) aggregated economic impacts. The related welfare loss reaches 36, 65 and 122 €billion at 1.5°C, 2°C and 3°C global warming, respectively. More than 80% of the mortality related welfare loss is estimated for southern EU regions. It should be noted that the share of human mortality loss to the total economic impact depends strongly on the appreciation of the economic value of life.

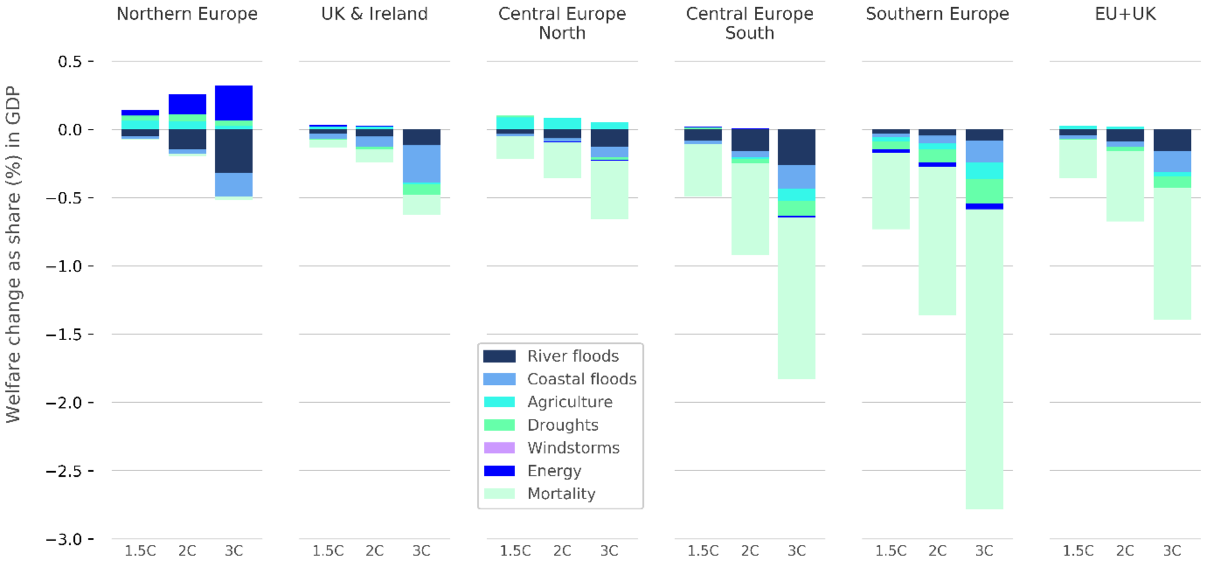

Figure 31. Welfare loss (% of GDP) from considered climate impacts at warming levels for the EU and the UK, and for macro regions (see Approach). The results represent change in welfare if warming levels would act upon current economy, compared to current economy under present climate.

River and coastal floods are the second most significant source of welfare loss in the EU, particularly in northern and central EU regions (Figure 32). Flooding impacts constitute 8.5 €billion of welfare loss with 1.5°C global warming, which increases to 16 €billion with 2°C and 40 €billion with 3°C global warming. It should be noted that sea levels will continue to rise long after climate has stabilised at a specific warming level, e.g. sea levels with 2°C in 2160 will be much higher than with 2°C in 2060. This means that coastal flood impacts projected here for a warming level are very conservative.

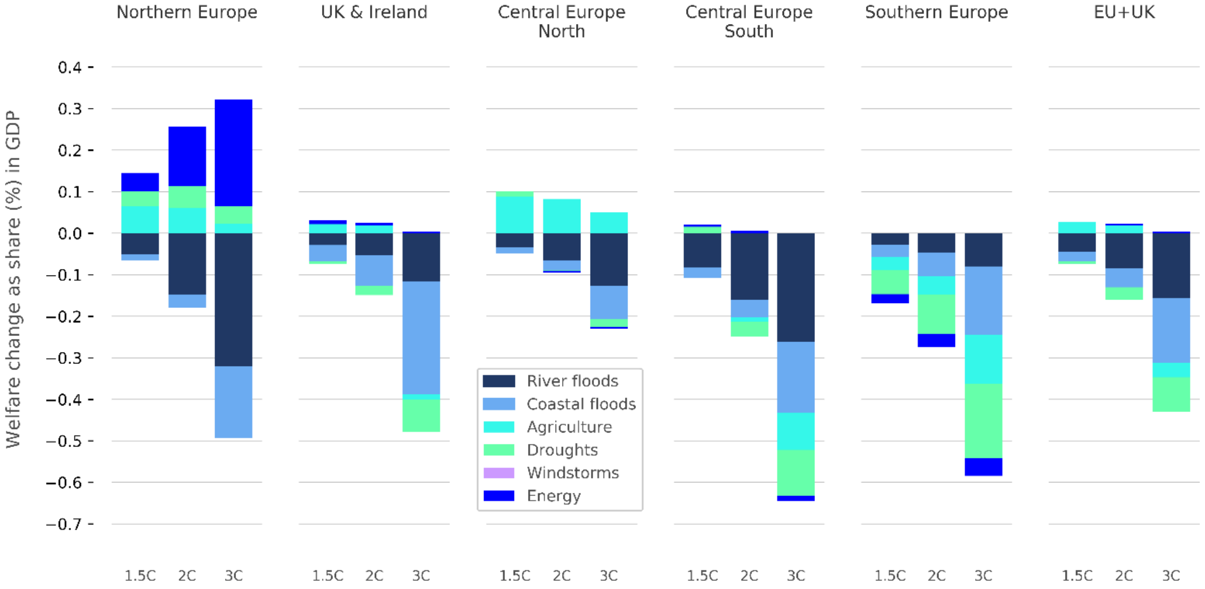

Figure 32. Welfare loss (% of GDP) from considered climate impacts excluding human mortality at warming levels for the EU and the UK, and for macro regions (see Approach). The results represent change in welfare if warming levels would act upon current economy, compared to current economy under present climate.

Changes in drought impacts lead to an increase in welfare in northern Europe, but become a source of welfare reduction in southern and western EU regions. With 1.5°C global warming the overall welfare loss from drought is limited to 0.7 €billion, but it grows to 10.6 €billion with 3°C global warming. Changes in agriculture yield also result in an increase in welfare in the north and a reduction in the south of Europe. For the EU and UK this results to a small positive welfare effect at low levels of warming (1.5°C and 2°C), which is reversed at higher levels of warming (3°C). The energy model simulates a positive effect of global warming on energy supply in the north and an opposite trend in the south. These regional effects are balanced at 1.5°C and result in a small increase in EU welfare at 2°C and 3°C global warming.

The north-south divide

There is a clear north-south divide in the regional distribution of welfare losses. The sum of impacts in northern regions are relatively small or even positive (e.g. northern Europe with 1.5°C and 2°C) as these regions experience gains from climate change for some of the sectors considered (agriculture, drought, energy supply). In southern EU regions the impacts are mostly negative. As a result, aggregated welfare losses in southern regions are several times larger compared to those in the north of Europe.

Spill-over effects from climate impacts in the rest of the world

The EU is not only affected by climate change impacting upon its economy, but also indirectly through international trade with countries that also experience climate-related damages. The findings of PESETA IV confirm a more comprehensive analysis performed in PESETA III, which showed that international spill-over effects could increase the internal EU welfare loss by approximately 20%.

Approach

The economic analysis has been made with a multi-sector, multi-country computable general equilibrium model (Climate assessment General Equilibrium, CaGE model) that integrates the various climate impact channels in a consistent way. The CaGE model was applied in a comparative static context, where future climate affects the economy as of today. The resulting estimates thus address the question: "How would today's economy be affected if global warming would occur today?"

Some of the main features of the interface between the damages for impact categories and the economic modelling include damage to capital stock, sectoral productivity reduction, and change in consumption.

The economic consequences are estimated in terms of welfare (consumption) changes using as input the direct damage estimates from the different impact categories. This includes damage to capital stock, sectoral productivity reduction, and changes in consumption. Welfare loss is in general larger than the direct damages because it accounts for indirect effects in the rest of the sectors of the economy (e.g. agricultural yield losses impacting the agro-food industry). Welfare loss is expressed in € (2015 value) as well as a share (in %) of GDP. Climate impacts happening in the rest of the world will also affect the EU via international trade. In PESETA IV the possible scale of international spill-overs due to impacts in the agriculture sector in the rest of the world is simulated with the CaGE model. More details in Szewczyk et al. (2020).

16 Limitations and way forward

The PESETA IV approach offers a number of advantages, including consistency in the use of socioeconomic and climate change scenarios across a wide range of sectoral impact and damage models. Nevertheless, modelling future climate impacts at the European continental scale involves inevitable simplifications, with considerable uncertainties in the models and datasets representing climate change, exposure and vulnerability of ecosystems, people and economic sectors. The main limitations are discussed below. Limitations specific to the individual impact assessments are described in the Technical Reports of each impact analysis, as well as in the scientific literature underlying the analyses. Ongoing and future work to address these limitations will strengthen the estimates presented in this report, including a broader coverage of impact categories and the use of ranges and confidence intervals.

Emission pathways, warming levels and climate projections

The project assumes that impacts at a certain warming level can be derived from transient climate projections, rather than climate projections that stabilise once a warming level is reached. By considering two RCPs, the uncertainty in the pathway to reach the warming levels is partly accounted for, but possible delayed effects on climate and consequent impacts after climate stabilisation are not accounted for. Current literature suggests that for most climate variables these effects are smaller than the variability in the climate projections. The time dimension, however, remains critical for time-delayed processes such as sea level rise, which will continue long after climate has stabilised at a certain warming level.

The use of two RCPs and a climate ensemble with 22 model realisations aims to characterise the uncertainty regarding future climate projections. However, the ensemble might still underrepresent the real uncertainty in future climate conditions.

Climate projections show bias in reproducing present climate. Bias-correction is applied to adjust for this, but this requires high-resolution observations of past climate conditions. This is currently only feasible for temperature and precipitation, while other variables required by some impact models are not corrected.

Coverage of impacts

The project is not comprehensive in the coverage of climate impacts in Europe. Even if eleven important climate impact mechanisms have been assessed, many potential consequences of global warming are not quantified. Impacts on terrestrial ecosystems and their services are only partially captured, while those on aquatic and marine ecosystems are not assessed. Climate change will impact food production beyond crop production, including effects on livestock, fisheries and aquaculture. Impacts on human health are not limited to mortality from temperature extremes, but also include effects on human mortality and morbidity from less extreme non-optimum background temperatures, air quality, and water- and vector-borne diseases. Sea level rise and rising coastal extremes will also result in increased erosion, loss of coastal ecosystems, saltwater intrusion and damage to port and maritime transport infrastructure. Apart from river flooding that is considered, climate change will affect pluvial and flash flooding from local intense precipitation. The PESETA IV energy analysis focuses on energy supply, while climate change will also drive changes in the demand for energy. Impacts on key economic sectors such as transport, tourism and labour productivity are not evaluated. Climate change could further induce the displacement of people, increase the risk of conflicts and have effects on security, yet it is very challenging to assess these consequences. Climate tipping points, or thresholds that, if passed, could have irreversible and catastrophic consequences, are also not considered. The project performed assessments of impacts for several climate extremes (heat and cold waves, drought, windstorms, river and coastal flooding), yet some sector impact analysis (e.g., energy supply, agriculture) do not fully capture the effects of such extremes and changes therein. Finally, due to the spatial domain challenges this would pose to the modelling activities, PESETA IV does not cover impacts in the EU's outermost regions.

Adaptation modelling

Modelling adaptation, especially at pan-European scale also remains a challenging task. The costs and benefits of adaptation are explicitly modelled for two impact categories only. Future work could try to include adaptation modelling for a wider range of impact categories. Such assessments should mainstream the involved policy areas, considering also stakeholders and users (both private and public), who currently face the adaptation challenge.

Including all these issues would provide a more complete understanding of the totality of risk posed by climate change on the EU and the potential for mitigation and adaptation to reduce or avoid impacts.

The cost-benefit analysis of adaptation remains also a challenging area, whose results are highly sensitive to many implementation choices, such as the discounting of investment costs in the shorter-term vs adaptation benefits that grow in time.

Uncertainty in impacts

Results in this report are primarily presented as point estimates that reflect the most likely outcome of the ensemble projections. For some sectors, ranges are provided based on the spread in the climate model projections. Uncertainties in the estimated biophysical impacts due to the conceptualisation and parameterisation of biophysical models is not accounted for as only one model is used per impact category. Using an ensemble of biophysical impact models, as done by the Inter-Sectoral Impact Model Intercomparison Project[1], might better represent the uncertainty of the biophysical impacts.

The economic valuation of impacts is another major source of uncertainty, in large because of the paucity of observations on losses in many sectors. This affects both the estimation of baseline economic losses and their projections under future climate and socioeconomic scenarios. Information regarding the physical and economic impacts of past climate and weather events, with a high spatial resolution, is required to improve the conceptualisation, calibration and validation of the various impact models. However, data collection and recording in Europe is heterogeneous and the available loss databases vary in their level of completeness and detail, or are not publicly available. Available information from national sources has to be homogenised and made available for climate impact research in order to better assess the scale and scope of climate risk in Europe.

It is therefore important to stress that PESETA IV results are not to be interpreted as forecasts or predictions of climate impacts for specific local areas, regions or countries. In particular, the purpose of this study is not to make a climate impact and adaptation assessment for EU member states, regions or cities. Rather, its purpose is to provide a pan-European perspective of the main patterns of climate impacts and potential of adaptation.

The further exploration of uncertainties in the risk analyses, including the development of probabilistic impact projections and representation of tail (low probability high impact) risk, will further strengthen the PESETA IV results.

Further integration across models

Some of the models are soft-linked mainly by using the output of one biophysical model as an input in another model (e.g. connection between water model and energy supply model: the hydrological simulations are used to assess the hydropower potentials). Furthermore, there exists a series of overlaps in the coverage of sectoral impacts for some of the biophysical models (e.g. impacts in the agriculture sector are considered also in the drought analysis).

Addressing those issues would require additional integration between the models. The plan is to identify the most relevant interconnections between the models (i.e. those that can substantially change the results) and try to improve the integration of the overall JRC PESETA modelling system. Past experience in integrated assessment models can be very useful in this respect.

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[1] https://www.isimip.org/

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