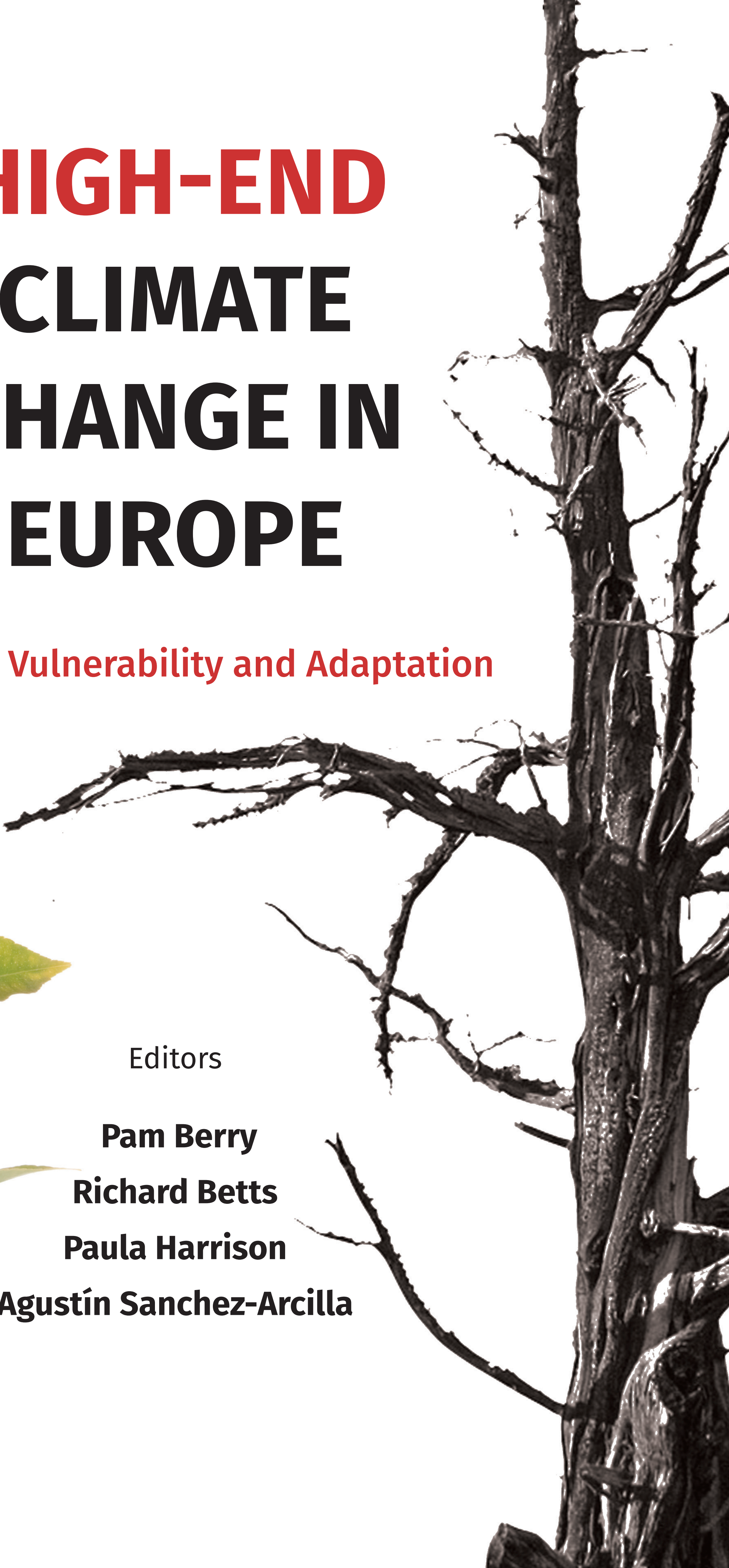
HIGH-END CLIMATE CHANGE IN EUROPE

Impacts, Vulnerability and Adaptation



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Impacts, Vulnerability and Adaptation

Berry, P.M., Betts, R.A., Harrison, P.A. and Sanchez-Arcilla, A. (Eds.)

This policy booklet, HIgh-End Climate Change in Europe, is based on "work in progress" by researchers from the IMPRESSIONS, HELIX and RISES-AM projects. While it has been commented on by expert stakeholders and researchers, it has not been subject to a full detailed peer review. The accuracy of this work and the conclusions reached are the responsibility of the authors. Decision-makers should therefore view the research presented here as a contribution to the wider research base; decisions should be informed by this wider research base rather than these early conclusions of individual projects.

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IMPRESSIONS

helix www.helixclimate.eu

RISES-AM- EU Research Project

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Foreword

Prof. Jean Palutikof

Jean Palutikof, Professor and Director, National Climate Change Adaptation Research Facility, Griffith University, Australia

The European Union is funding three major international research projects - HELIX, IMPRESSIONS and RISES-AM - to assess the possible impacts of "high-end" climate change and the potential for adaptation. Together, these three projects address some of the key issues around climate change and its management. They bring up-to-date and detailed research results from climate models and impact analyses together with expert knowledge about response options in adaptation and mitigation to deliver end-to-end understanding of the risks from climate change and how these can be dealt with. It is only through such comprehensive and integrated studies that effective solutions to climate change can be achieved.

From my perspective based in Australia, there are some interesting parallels between the findings in this Policy Booklet and what is happening in Australia, and some differences. The vast majority of the Australian population, and the associated infrastructure, are located along the coast, and therefore it is sea-level rise and the effects of storm surge and wave storms that truly concentrate the minds of policymakers - questions around legal liability, who pays, and when, where and how to act. Something like half the current budget of my organisation, the National Climate Change Adaptation Research Facility, is devoted to coastal risks. The sections on coastal protection in this Policy Booklet resonated strongly.

Similarly, the section on health has a focus on heat that carries strong messages for anyone working in climate change in Australia. Every summer brings new extremes and broken records, and in fact for the summer of 2016/17 it has been calculated that 205 records were broken. This booklet concludes that there will be 'limits to adaptation to higher temperatures' and there is a message there for Australia, where summer temperatures in many places already challenge the capacity of humans and animals to adapt.

But in some respects there are important differences in where the emphasis lies in Europe and in Australia. The potential for vector-borne diseases to spread southwards and for outbreaks to become more common is an important risk for Australia – for people's health and well-being, the economy and the natural environment. Bushfire outbreaks are expected to become more common and more intense as temperatures increase and the environment dries – and indeed there is evidence that this is already happening. Whether or not it's called autonomous or planned adaptation or simply disaster preparedness, people are now more aware of their risk from bushfire, and more likely to prepare a proper plan of action.

Perhaps the greatest difference is the sense in Australia that some of the risks are close, indeed already with us. Whereas in Europe there is a little more time before impacts become strongly negative. The two great challenges for Australia are, first, to build acceptance of the risks and the need to act amongst communities that can be sceptical of the reality of climate change and, second, to transition from planning to adaptation action. It seems that many thousand adaptation strategies have been written, but that the positive adaptation actions can be counted only in the few hundreds.

HELIX, IMPRESSIONS and RISES-AM provide comprehensive knowledge to underpin effective action to address the risks of climate change. There is considerable likelihood that, in the absence of such knowledge, actions to address climate change will be maladaptive – adaptations will increase greenhouse gas emissions and actions to address short-term risks will create path dependencies in the future. The existence of well thought through Policy Booklets such as this will help to guard against such an eventuality.

Glossary of Acronyms

AEI – Adaptation Effort Indices a measure used to highlight management need for species conservation

AoC – Areas of Concern a measure used to highlight where climate becomes unsuitable for >75% of the species modelled

CanESM2/CanRCM4 - Canadian Centre for Climate Modelling and Analysis Earth System Model version 2 driving Regional Climate Model version 4

CAP - Common Agricultural Policy

CETA - Comprehensive Economic and Trade Agreement

CNI - Connectivity Necessity Index a measure of areas that would benefit the most from habitat connectivity as an adaptation strategy

CoP 21 - UN Framework Convention on Climate Change Conference of the Parties 21st yearly session. COP21 was 30 November - 12 December 2015 in Paris and is where the 'Paris Agreement' was negotiated and agreed by 174 countries. The Adaption of the Paris Agreement reads "...holding the increase in the global average temperature to well below 2°C above preindustrial levels and pursuing efforts to limit the temperature increase to 1.5°C"

CSDP - Common Security and Defence Policies

cVeg DG DEVCO – European Commission Directorate General for International Cooperation and Development

DG CLIMA – European Commission Directorate-General for Climate Action

DIPECHO - Disaster Preparedness European Commission's Humanitarian Aid and Civil prOtection department

ENP - European Neighbourhood Policy

ERDF – European Regional Development Fund

FAP - EU Forest Action Plan

FS - EU Forest Strategy

GAMM- Global Approach to Migration and Mobility

GCM-RCM – General Circulation Model with an embedded Regional Climate Model for higher spatial resolution

GDP - Gross Domestic Productivity

GES – Good Environmental Status (by 2020) is the main goal of the European Union's Marine Strategy Framework Directive

GFDL - Geophysical Fluid Dynamics Laboratory

GISS - NASA Goddard Institute for Space Studies

GISS+EC-Earth-HR - high-resolution version of the EC-Earth climate model driven by sea surface temperatures from the GISS climate model

HadGEM2-ES – Hadley Centre (of the UK's Met Office) Global Environment Model, version 2, Earth System configuration

HadGEM2-ES/RCA4 - Hadley Centre Global Environment Model, version 2, Earth System configuration, driving with Rossby Centre Regional Atmosphere Model 4

HECC – High-End Climate Change

HELIX – High-End CLimate Impacts and eXtremes research project

IMPRESSIONS – Impacts and Risks from High-End Scenarios: Strategies for Innovative Solutions research project

IPCC WGII AR5 – Intergovernmental Panel on Climate Change Working Group 2 Assessment Report 5

IPSL - Institut Pierre Simon Laplace LULUCF - Land Use, Land Use Change and Forestry

IPSL-CM5A-MR/WRF - IPSL Climate Model version 5, medium resolution, driving the Weather Research and Forecasting model

IPSL+EC-Earth-HR - High-resolution version of the EC-Earth climate model driven by sea surface temperatures from the IPSL climate model

IPSL+HadGEM3-HR - High-resolution version of the 3rd Hadley Centre Global Environment Model driven by sea surface temperatures from the IPSL climate mode

NBS – Nature-Based Solutions

ND-GAIN - University of Notre-Dame Global Adaptation Index

NWRM - Natural Water Retention Measures

ORCHIDEE - Organizing Carbon and Hydrology in Dynamic Ecosystems [land surface model]

PAs – Protected Areas [of land use and habitat conservation]

RCM – Regional Climate Model, typically with higher spatial resolution than global General Circulation Model (GCM)

RCPs - Representative Concentration Pathways the four greenhouse gas emission trajectories used in the Intergovernmental Panel on Climate Change (IPCC) Fifth Assessment Report. See SSPs also.

rIAM – Regional Integrated Assessment Model for examining the interactions at the Regional Scale between climate change, the land, water and atmosphere responses of the Earth System, and human economics

RISES-AM – Responses to coastal climate change: Innovative Strategies for high-End Scenarios Adaptation and Mitigation research project

RSLR – Relative Sea-Level Rise

RUG – Regional Urban Growth model

SDGs – UN Sustainable Development Goals

SLR – Sea-Level Rise

SWL - Specific Warming Level

SSP - Shared Socio-economic Pathways the five global development storylines combined with quantitative social drivers used in the Intergovernmental Panel on Climate Change (IPCC) Fifth Assessment Report. See RCPs also.

TCI - Transnational Climate Impacts Index [of Stockholm Environment Institute]

TTIP - Transatlantic Trade and Investment Partnership

UHI – Urban Heat Island air temperature is measurably higher in cities than it is in the surrounding countryside

Executive summary

In 2013, the European Commission funded three major projects to assess climate change impacts, adaptation and vulnerability for "high-end scenarios" - defined as global warming exceeding 2°C relative to pre-industrial. These projects are: HELIX (High-End cLimate Impacts and eXtreme); IMPRESSIONS (IMPacts and REsponses from high-end Scenarios: Strategies for Innovative SolutiONS) and RISES-AM (Responses to coastal climate change: Innovative Strategies for high-End Scenarios - Adaptation and Mitigation), which between them involve over 150 researchers from leading scientific institutions across Europe and also in Africa, Asia and America.

Drawing on a very wide range of expertise from many disciplines in both the natural and social sciences, we are developing new understanding of the implications and risks of exceeding 2°C, the challenges and opportunities of adaptation to such a warmer world, and the extent to which risks can be reduced if warming is held as close as possible to 1.5°C.

We are examining impacts and adaptation relevant to a number of areas addressed by policy: food, freshwater, forestry, coastal protection, nature conservation, urban areas and infrastructure, human health and foreign policy. We are also considering cross-cutting impacts, challenges and opportunities for transformational change as a response to multiple, interacting risks.

This report presents the findings of these three projects as of early 2017.

- The existence of future food production tipping points for the European agriculture sector depends on the complex scenario-dependent inter-play between future food demand, net food imports, and European agricultural productivity.

- European land-use appears more sensitive to future socio-economic change than climate change. The spatial distribution of impacts on arable and livestock systems will depend on the relative impacts of future change on agricultural and forest profitability (locally and regionally) and the availability of irrigation water. Increasing water stress may lead to increased competition for water in many catchments, as a result of reduced water availability due to climate change and/or increasing water demand (from agriculture, public water supply and the environment).

- Autonomous adaptation is expected to feature northwards and north-westwards shifts in agricultural systems as land suitability and productivity change. High-end climate change may pose important challenges and opportunities for the livestock sector in Europe. Heat stress is likely to increase in indoor and outdoor livestock and poultry, including during transportation.

- Many species and habitats will be directly or indirectly (positively and negatively) affected by high-end scenarios. Many pollinators, critical for producing good crop yields, may lose climate space, especially in southern Europe.

Agriculture

- High-end climate change will potentially have strong and lasting effects on the agricultural sector and consequently on food markets and food security across the globe, and also in Europe.

Freshwater

- Annual mean runoff is generally projected to increase in northern Europe and decrease in southern Europe. In the central latitudes of Europe, there is no clear agreement between models on either increases or decreases in annual mean flows.

- In projections with a high emissions scenario, the population annually affected by river floods in Europe increases from approximately 216,000 people per year in 1976-2005 to between 500,000 and 640,000 per year around 2050, and 540,000 to 950,000 per year around 2080. The projected damage costs of river flooding increases from approximately 5.3 B€ per year in 1976-2005 to 20 to 40 B€ per year around 2050, and 30 to 100 B€ per year in 2080. Much of the uncertainty range arises due to socio-economic scenario assumptions, especially the economic damages.

- Adaptation efforts aimed at trying to avoid floods may not be effective in the long term. An alternative approach to reduce the flood risk could favour measures targeted at reducing the impacts of floods, rather than trying to avoid them.

- Drought prone areas increase with global warming particularly in the Mediterranean region. Low flows are projected to become less extreme in northern Europe but more extreme in Southern Europe. In some cases, low flows may decrease even in areas where annual mean flows increase.

- Projected increases in the severity and duration of freshwater shortages, especially for the southern part of Europe, have several implications for agriculture, forest and ecosystems, domestic supply, power supply and tourism.

- Among the most impacted countries, there is a high model consensus that substantial areas of Spain are projected to face a large increase in the duration of extreme prolonged droughts.

Coastal protection

- Even if emissions and temperatures stabilise, sea-levels will continue to rise. Climate change mitigation may help to reduce the rate of sea-level rise to manageable levels, but adaptation is required to help cope with the residual rise.

- Coastal monitoring (e.g. tide gauges, beach surveys) is required to determine the environmental state, and whether acceptable thresholds of risk are being reached. This would help determine if and when adaptation needs to change in order to achieve the management goal.

- Intervention for successful adaptation will be most effective if it is bespoke, balancing financial, economical, societal, equitable, governance, legislative and environment interests. Soft engineering and nature-based solutions are increasingly encouraged for a sustainable coast, but have only been proven in a limited number of pilot cases. Further research is required into resources and effectiveness of nature based solutions (NBS). It is recognised that not everywhere can be protected.

- Flexibility is required in adaptation, with multiple choices to achieve a management goal (e.g. defined risk levels). Adaptation pathways provide one structured way to achieve this. These can be challenging to generate due to barriers in planning for adaptation.

- Governance, societal and cultural acceptance of flexible change present the greatest barrier for adaptation, particularly over the longer term (> 50 years). This is particularly difficult as it is hard to envisage and act on long-term change, when short-term needs are greater and more immediate than the long-term sustainability of the coast.

- Priorities will depend on policy criteria, ability to pay, societal preference and technological feasibilities. Areas with high exposure of people and assets (e.g. cities) demand more stringent protection and adaptation as risk levels are high. Lower population densities are less likely to be protected at the same level, and other adaptation options need to be explored. This will lead to equity issues, particularly if adaptation is paid from national budgets to which all citizens contribute.

Forestry

- Some climate-induced changes in European forests are expected to occur relatively smoothly over time, whereas others may occur as "shocks", passing thresholds or tipping points.

- In the climate change scenarios considered here, there is a clear north-south gradient regarding the impacts of climate change on forests, excluding other factors such as CO_2 physiological effects and nitrogen deposition. High latitudes and elevations potentially benefit from climate change, and forests at low latitudes potentially lose as a result of projected shifts towards drier conditions, particularly in the Mediterranean region. Different regional climate outcomes could result in different impacts.

- Increased CO_2 concentrations have a potentially positive effect on forest productivity. In the absence of acclimation of trees to elevated CO_2, this driver could modulate the impact of climatic change by either further increasing forest productivity (e.g., at high latitudes or elevations), or at least partly compensating for negative climatic effects.

- Forestry can be adapted to the changing climate by switching to climatically better adapted species, and moving towards forestry systems that include more than one tree species at the stand scale.

- European forests and forest products are significant contributors to the European greenhouse gas balance, constituting a major carbon sink that can help to reach EU climate targets.

Nature conservation

- Under high-end climate change scenarios, the combined effects of climatic and socio-economic change pose high risks to biodiversity across Europe. There is considerable risk of major transformations of many ecosystems in southern Europe.

- The greatest scope for gains in biodiversity arises from potential land abandonment, mainly in northern Europe. The magnitude and uncertainty of climate and land-use change in parts of southern Europe, imply a need for intervention to avoid the loss of key connecting habitats and the worst possible outcomes for conservation.

- Rates of climate change under high emissions scenarios would largely be in excess of the ability of species to keep up through dispersal, although the extent to which this becomes a problem will depend on the length of time the climate continues to warm.

- Support for nature conservation at local and national scales has been demonstrated to be an important factor in maintaining the scale and connectivity of natural areas.

- Land for nature conservation fundamentally depends on food demand and the intensity of agricultural production, with intensive production allowing land-sparing for conservation, and extensive production limiting the scope for nature conservation, except through multifunctional land-uses.

- Protecting conservation areas to prevent intensification in one location may lead to knock-on effects on other habitats elsewhere, for some scenarios.

- Nature-based approaches can support transition away from non-renewable to renewable natural capital and can be associated with increased co-production and provision of ecosystem services. The widespread use of nature-based solutions provides many opportunities for synergies across policy objectives, including benefits to both climate change adaptation and mitigation. As such, nature-based solutions can enable the transition from a resource-intensive towards a more resource-efficient and sustainable development model model.

Human Health

- Higher temperatures could have significant impacts for health and wellbeing including human comfort, particularly in southern Europe.

- Under high emissions scenarios, high temperatures after mid-century would be expected to alter patterns of daily living and working.

- Autonomous adaptation could offset significant impacts but there will be limits to adaptation to higher temperatures.

- Adaptation strategies relating to new build and retrofitting of dwellings has implications for mitigation policy unless energy intensive space cooling is avoided.

- Climate change is projected to increase child undernutrition in sub-Saharan Africa and South Asia, but research is needed to understand the full implications of the high-end scenarios.

Urban

- Artificial surface extent could vary from about 4% of the European land area today, to approximately 4% to 9% of that area by 2100, depending on the socio-economic scenario.

- Population change is a key driver of future artificial surface expansion. However, changes to the demographic profile of this population, their residential preferences and planning legislation have the potential to restrict or magnify patterns of growth. A declining population does not imply a static artificial surface extent in the presence of changing residential preferences.

- The contrasting residential profiles of each socio-economic scenario influence the extent and location of future artificial surfaces. The dense urban networks of Belgium, the Netherlands, western Germany and southern United Kingdom promote concentrations of future suburban development. This is in contrast to the 'hotspots' of development that are more sparsely distributed across, for example, Spain, Portugal and the Nordic countries.

- Sprawling urban development could place greater pressure on sensitive ecosystems as the population in close proximity to protected areas, water bodies and coastal regions increases.

Foreign policy and international development

- Transnational climate change impacts could have substantial effects on Europe. High-end scenarios could imply increased systemic effects of climate change, including cross-sectoral and transnational climate impacts. However, research on the physical as well as governance aspects of transnational climate impacts is still in its infancy.

- Transnational climate impacts still play a minor role in the EU, as well as in Members States' adaptation policies. The potential international dimension of climate impacts may provide incentives for more collaboration between EU Member States, as well as between the EU and other parts of the world.

Policy Insights

- Either avoiding or exceeding 2°C global warming could pose unprecedented challenges as well as new opportunities for societal transformation. Innovative approaches in science and policy may be required. Integrated strategies for these new social-ecological conditions could be achieved, and ensured in the long run, by linking climate-oriented, practical, systemic solutions to sustainable development.

- Sustainable solutions are those that are able to overcome multiple trade-offs between ecological integrity and socio-economic goals in ways which can be turned into positive synergies. Clusters of sustainable solutions can be identified, tested and implemented by integrating multiple forms of knowledge and values in concrete places following transformative visions of the kind of world in which we want to live.

- Conventional and additive approaches focusing on single sectors, scales or either adaptation or mitigation without considering long-term sustainable development may not be enough to cope with the mounting risks and challenges of high-end climate change. Innovative approaches entail combining multiple systems of solutions that not only solve present problems but also learn how to transform current systems arrangements so as to prevent them occurring again.

- Conventional policy appraisal methods are designed for relatively short-term, well-understood policy choices in single sectors and are not feasible for transformative approaches combining multiple systems of solutions. They face severe limitations for assessing the impact of very long-term decisions about adaption and mitigation in the face of large climate risks.

Context and Introduction

Policy background

Although the Paris Agreement commits its signatories to holding global warming to well below 2°C and pursuing efforts to limit warming to 1.5°C, the emissions pathways implied by the current Nationally Determined Contributions would still lead to warming well in excess of 2°C. This will inevitably lead to further ongoing sea-level rise and alter weather patterns around the globe. It is thus vital that decision-makers have access to reliable scientific information on these uncertain, but potentially high-risk, scenarios of the future. This information should inform the need for transformative strategies to address potential synergies and trade-offs between adaptation, mitigation and sustainable development. Policy-makers, businesses and other decision-makers need to understand impacts at a range of levels of global warming, and also begin to plan ahead for adaptation to changes in climate associated with higher levels of global warming. This requires coherent information on the potential conditions which may need to be adapted to, and the consequences of different courses of adaptation action. Alongside this, ongoing international negotiations on limiting global warming also require clear information on the consequences of different levels of climate change.

Previous state of the art

While numerous studies have explored the impacts of climate change at a variety of spatial scales on different policy sectors (e.g. IPCC, 2014), much of the information is conflicting, unclear, of unknown levels of certainty and difficult to apply to inform decisions.

The information currently available is often inconsistent across scales. Different methods are used for addressing different questions, and lack of consistency can lead to confusion and potentially exposes decision-makers to risks of poor decisions, either because incomplete information is available or because the available information is too varied and inconsistent to be useful.

Moreover, most studies ignore potential interactions with other sectors. Cross-sectoral interactions are important since changes in one sector can affect another sector either directly (e.g. land-use change affects regional hydrology) or indirectly through policy (e.g. measures designed for coastal flood defence also impact on coastal habitat) (Harrison et al., 2015). Ignoring cross-sectoral interactions is likely to lead to misrepresentation of impacts, and consequently to poor decisions about climate adaptation (Harrison et al., 2016).

Many previous studies report the impacts of climate change under current socio-economic conditions, but in fact impacts will interact with those associated with continuing socio-economic and political changes, in potentially complex, non-additive ways (Holman et al., 2015). This highlights the importance of assessing multiple interacting pressures (both climatic and socio-economic) to understand the vulnerability of human and environmental systems. Previously, estimates of vulnerability have been undertaken at global scales at relatively coarse resolutions, whilst analyses at local scales have been limited, where there was no information on high-resolution projected pressures or associated responses. For example, in the case of sea-level rise impacts at the global scale, most existing approaches only consider retreat or defence interventions for a limited number of coastal typologies, mainly vulnerable low-lying coasts with limited inclusion of existing infrastructures (or planned ones) and the socio-economic activities that the coast supports.. Moreover, the interventions considered are based on conventional coastal engineering (additional nourishment or higher coastal structures). Nevertheless, there are many local scale examples based on coastal restoration (partial re-wilding) and managed re-alignment. Such nature-based approaches have received limited attention at the regional scale and are lacking at the global scale, although their potential under future climates remains large.

These issues are particularly important under high-end climate change as such scenarios may lead to amplified interdependencies between different sectors as well as between regions, including countries beyond the EU's borders (e.g. via food and resource supply chains or large-scale migration). Furthermore, high-end scenarios may push societies in Europe and elsewhere well beyond the limits of adaptation (Simonsson et al., 2011), but the nature of these limits remains highly uncertain (Watkiss et al., 2015), creating a significant challenge for both science and decision-making.

Advancing the science and its application

The EU-funded projects HELIX, IMPRESSIONS and RISES-AM address these issues with new scenarios of climate change impacts, adaptation and vulnerability designed to be more integrated and internally-consistent than previous research. The research covers a very wide range of scales from global to local, making use of insights from stakeholders to make the results and advice relevant to decision-making.

The projects assess a wide range of sectors and systems, including agriculture, freshwater, coasts, urban areas, infrastructure, human health, biodiversity and foreign policy. Interactions between these are of particular interest. The main focus is on scenarios of climate change above 2ºC global warming, particularly 4ºC or even 6ºC warming, although some assessment of impacts at 1.5ºC is also being carried out.

Much of the work assessing impacts, adaptation and vulnerability in Europe is from the continental scale down to individual local case studies. The projects also assess these issues across the globe, including particularly vulnerable regions and/or densely populated regions. The role of climate change as an additional factor in wider issues, such as security, health and migration, are of key interest.

We have worked closely with a range of stakeholders to identify the technical and political problems they face when making decisions about complex and uncertain issues, and the information, tools and methods they need to overcome these barriers. This participatory approach aims to ensure that the outputs of the projects meet the needs of decision-makers, helping them to make long-term plans based on a full awareness of climate risks, adaptation limits and adaptation/mitigation opportunities. Locally-relevant information, such as details of coastal interventions to manage flooding risk, is being sought and implemented by combining advanced scientific knowledge with local stakeholders' criteria and preferences.

A major issue for climate policy is that it requires decision-making in the face of large uncertainties. Although there is confidence in the basic principle that ongoing emissions will cause further warming at global scales, the local implications of this are far from clear. Global warming of, for example, 2ºC, could be associated with a wide range of changes in climate in Europe and individual countries or cities. Adaptation decisions, therefore, need to be resilient to many possible future climate states, so the projects assessed a number of different regional outcomes. Moreover, vulnerability and adaptive capacity will depend on societal factors which again are complex and hard to project, so a number of different scenarios are assessed. The timing of reaching a particular climate state is of key importance – for example, even if 2ºC is reached eventually, if it is reached slowly then there may be more scope for adaptation than if it is reached quickly. This is critical for natural systems which are unlikely to be able to track rapid changes in climate (see Nature Conservation), but also for social systems in which decision-making and governance arrangements may need to transform. To address such issues, we are improving how adaptation is modelled by incorporating a more comprehensive representation of associated constraints, triggers, time lags and consequences, and developing new models which simulate adaptation as a process by representing the behaviour of decision-makers, firms and institutions as agents who learn and interact over different timescales.

It is also important not to assume that models give us a complete picture of future climate risks or societal states. With such complex systems, major changes may occur that are not captured by current model projections, physical or economic understanding or experience. We are investigating the potential impacts of passing tipping points in the climate system, such as a collapse of the Atlantic Meridional Overturning Circulation, and socio-economic shocks, such as collapse of financial markets or rapid shifts in human consumption.

Pathways are being analysed to assess the need for transformative strategies that take account of potential synergies and trade-offs between adaptation, mitigation and sustainable development. We are also evaluating how the new knowledge gained from the scenarios, impact modelling and pathways can be embedded within decision-making processes, so that effective climate governance plans can be conceived that deal with adaptation and mitigation in a synergistic way.

High-end scenarios

We assessed the impacts of climate change in a number of high-end scenarios. HELIX framed these in terms of Specific Warming Levels (SWL) – particular levels of global warming, such as 2ºC, 4ºC and 6ºC. Such a framing is often viewed as more accessible to decision-makers than the time-dependent scenarios that are often used, and indeed the Paris Agreement frames the policy objectives in terms of such warming levels, i.e. 2ºC and 1.5ºC. We used a large number of models of global and regional climate in order to capture a wide range of possible outcomes (Figure 1).

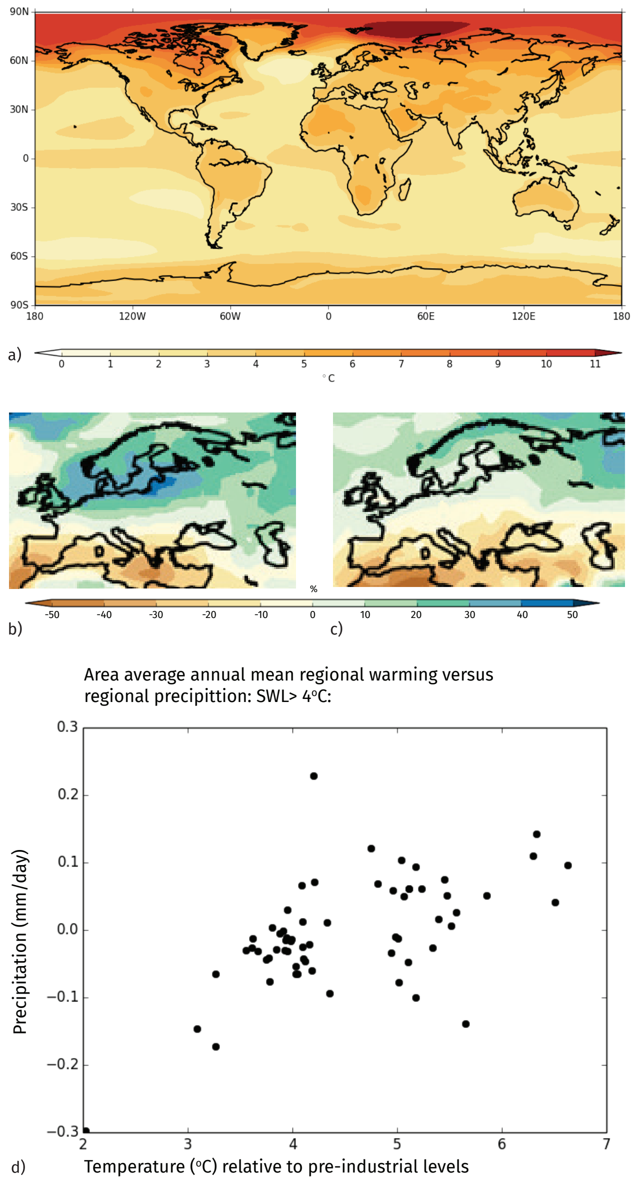

Figure 1. Patterns of projected climate change at 4°C global warming, across the world and over Europe, illustrating uncertainties. (a) Annual mean temperature change averaged across all models from the 5th Coupled Model Intercomparison Project (CMIP5). (b, c) Annual mean precipitation change in Europe simulated by two example climate models, illustrating different simulated precipitation changes. (d) Changes in European mean temperature and precipitation for 54 individual climate simulations. All results are means over 30-year periods centred around the time of global warming passing 4°C relative to pre-industrial.

Nevertheless, since the timing of reaching such warming levels is crucial for some of the impacts and also for assessing vulnerability and adaptation, time-dependent scenarios are still necessary. In HELIX, the range of times of reaching SWLs was determined using the Representative Concentration Pathways (RCPs), which are scenarios of changes in atmospheric composition that could result from various future emissions and various different strengths of feedback in the climate system. IMPRESSIONS and RISES-AM also used climate projections based on the RCPs. Any given future emissions scenario may lead to a wide range of future changes in CO_2 in the atmosphere, depending on the extent to which natural carbon sinks become strengthened or weakened by climate change itself. Conversely, any particular future trajectory of concentrations may result from a range of different emissions scenarios, again depending on the strength and sign of feedbacks. The possibility of non-linear changes and the passing of 'tipping points' in ecosystems adds further uncertainty. Changes in the concentrations of other greenhouse gases may also depend on feedbacks with climate change, complicating the relationship with emissions. Since the climate models used in our projects were driven by concentrations rather than emissions, the resulting climate states are compatible with a range of different emissions scenarios. Most of our analyses examined the scenario with the greatest increase in greenhouse gas concentrations known as RCP8.5 (Figure 2), denoting a radiative forcing (change in the Earth's energy balance) of 8.5 Watts per Square Metre, Wm^{-2} – an Earth System Model analysis shows that this would be associated with global CO_2-eq emissions approaching stabilisation at between 20 and 30 GtC of carbon by 2100 (two to three times the current emissions of about 10GtC). (Jones et al, 2013). We also looked at scenario RCP4.5 (a radiative forcing of 4.5 Wm^{-2}). Although this is still an increase in concentrations, holding the concentrations to these levels would nevertheless require emissions to decrease to between 2 to 8 GtC by 2100 – CO_2 is only gradually removed from the atmosphere, so it continues to build up even if emissions reduce, until emissions become zero.

For future changes in society including economic conditions, the Shared Socio-economic Pathways (SSPs) provide a means for exploring uncertainties about how social and economic conditions might develop in the future and for considering how those changes might alter society's vulnerability to climate change and ability to adapt (O'Neill et al., 2015). They describe a set of alternative plausible trajectories of future societal development which pose challenges to adaptation and mitigation (Figure 3). The SSPs consist of five narrative storylines, a set of descriptive trends in demographics, human development, economy and lifestyle, policies and institutions, technology, and environment and natural resources, along with a set of quantifications for some key variables (e.g. population growth, GDP and urbanisation).

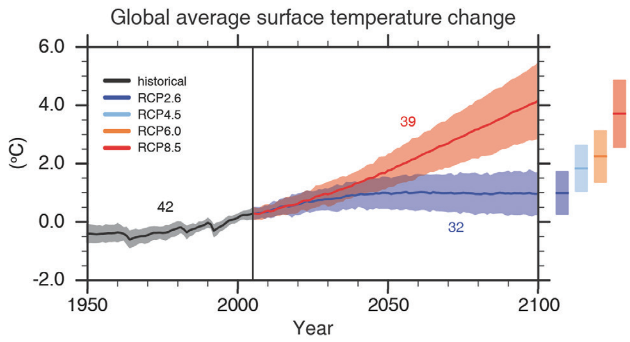

Figure 2. Changes in global mean temperature relative to 1985-2005 projected for the CMIP5 climate models, illustrating the range of uncertainty in rates of warming. The two plumes show the highest and lowest emissions scenarios, RCP8.5 (red) and RCP2.6 (dark blue). The bars on the right show the warming at the end of the century in these two scenarios and also two intermediate scenarios. The numbers next to the plumes show the number of climate models used for each projection or the historical period. Note that the temperature change shown here is relative to 1985-2010 – for changes relative to pre-industrial, 0.6°C should be added. Reproduced from Intergovernmental Panel on Climate Change 5th Assessment Report, Working Group 1 Summary for Policymakers. Copyright IPCC (2012).

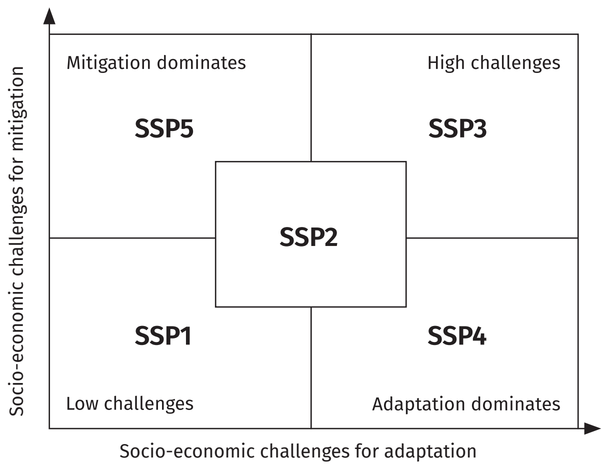

Figure 3. Graphical presentation of the Shared Socioeconomic Scenarios (SSPs). Adapted from O'Neill et al. (2015).

The global SSPs have been downscaled and extended for Europe by IMPRESSIONS (Kok and Pedde, 2016). These were further downscaled to regions within Europe by RISES-AM and IMPRESSIONS to provide improved regional specificity and greater temporal and sectoral detail. Only four of the five SSPs were downscaled (SSP2, the middle of the road scenario, was excluded as this is the least extreme ('high-end') of the scenarios with intermediate challenges for adaptation and mitigation). An overview of the European SSPs is given below (for completeness the global overview for SSP2 is included):

- SSP1 (Sustainability): There is a high commitment to achieve the sustainable development goals through effective governments and global cooperation, ultimately resulting in less inequality and less resource-intensive lifestyles. The European Union expands and is characterised by a high level of sustainability-oriented political and societal awareness, focusing on renewable energy and low material growth in a strongly regulated but effective multi-level governance structure.

- SSP2 (Middle of the Road, based on global narrative): The world follows a path in which social, economic, and technological trends do not shift markedly from historical patterns. Development and income growth proceeds unevenly across countries with globally connected markets functioning imperfectly. Global and national institutions work toward, but make slow progress in, achieving sustainable development goals.

- SSP3 (Regional Rivalry): Sparked by economic woes in major economies and regional conflict, antagonism between and within regional blocs increases, resulting in the disintegration of social fabric and many countries struggling to maintain living standards. Eventually the EU breaks down, and a highly carbon-intensive Europe emerges with strong regional rivalry and high inequalities.

- SSP4 (Inequality): Globally, power becomes more concentrated in a relatively small political and business elite. The EU increases commitment to find innovative solutions to the depletion of natural resources and climate change which initiates a shift towards a high-tech green Europe. However, there are increasing disparities in economic opportunity, leading to substantial proportions of populations having a low level of development. By 2100, Europe is an important player in a world full of tensions.

- SSP5 (Fossil-fuelled Development): People in this world increasingly rely on competitive markets, innovation and participatory societies to produce rapid technological progress and development of human capital as the path to sustainable development. Europe plays a leading role in the global economy, but this is coupled with the exploitation of abundant fossil fuel resources, including large-scale extraction of shale gas. Society places faith in geo-engineering solutions to counter environmental problems that emerge due to the over-exploitation of natural resources.

Agriculture

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Key messages

- High-end climate change will potentially have strong and lasting effects on the agricultural sector and consequently on food markets and food security across the globe, and also in Europe.

- The existence of future food production tipping points for the European agriculture sector depends on the complex scenario-dependent inter-play between future food demand, net food imports, and European agricultural productivity.

- European land-use appears more sensitive to future socio-economic change than climate change. The spatial distribution of impacts on arable and livestock systems will depend on the relative impacts of future change on agricultural and forest profitability (locally and regionally) and the availability of irrigation water. Increasing water stress may lead to increased competition for water in many catchments, as a result of reduced water availability due to climate change and/or increasing water demand (from agriculture, public water supply and the environment).

- Autonomous adaptation is expected to feature northwards and north-westwards shifts in agricultural systems as land suitability and productivity change. High-end climate change may pose important challenges and opportunities for the livestock sector in Europe. Heat stress is likely to increase in indoor and outdoor livestock and poultry, including during transportation.

- Many species and habitats will be directly or indirectly (positively and negatively) affected by high-end scenarios. Many pollinators, critical for producing good crop yields, may lose climate space, especially in southern Europe.

Policy Context

The Common Agricultural Policy (CAP) has three key objectives: (1) Viable food production to ensure a stable supply of affordable and quality food to the EU's 500 million citizens; (2) Sustainable management of natural resources (biodiversity, the landscape and soil quality); and (3) balanced territorial development. The CAP remains of key importance, contributing to more sustainable and inclusive growth, as one of the key objectives of the EU's 2020 Strategy.

Policy Insights

Can Europe meet its net food demands under high-end scenarios?

1. How might high-end impacts worldwide affect the EU food market (or other assets) and food security?

High-end climate change will potentially have strong and lasting effects on the agricultural sector and consequently on food markets and food security across the globe, and also in Europe. There are large differences between future outlooks in terms of both magnitude of climate change and type of socio-economic change, as well as between geographical regions. Regarding crop productivity, modelling of projected yields of wheat, maize and soy suggests that at global average temperature increases of 4°C (relative to pre-industrial temperatures) and the associated CO_2 increases and precipitation changes, EU-average yields could increase, although with some wide areas experiencing decreased yields (Figure 4). It should be noted, however, that such models do not consider the impacts of CO_2 fertilisation on the nutritional value of these crops nor changing patterns of cropping and the potential impacts of crop pests and pathogens – these could substantially impact yields, but current knowledge is not sufficiently advanced to enable their effects to be quantified.

IMPRESSIONS scenarios of socio-economic change represent large differences in Europe's relationships with the world and the consequent trade relationships that will affect European food markets and food security. The effect of socio-economic change is large on trade with more agricultural export and import in globalising worlds (SSP1 and 5), and less trade in regionalising worlds (SSP3 and 4).

2. Are there particular tipping points beyond which food production in Europe becomes compromised?

The existence of food production tipping points for the European agriculture sector depends on the complex scenario-dependent inter-play between future food demand, net food imports, and European agricultural productivity. Key factors determining this balance, which are captured within IMPRESSIONS, are:

- population, wealth and dietary preferences (influencing European food demand);
- agricultural policy (influencing food security, agricultural intensity and agricultural employment);

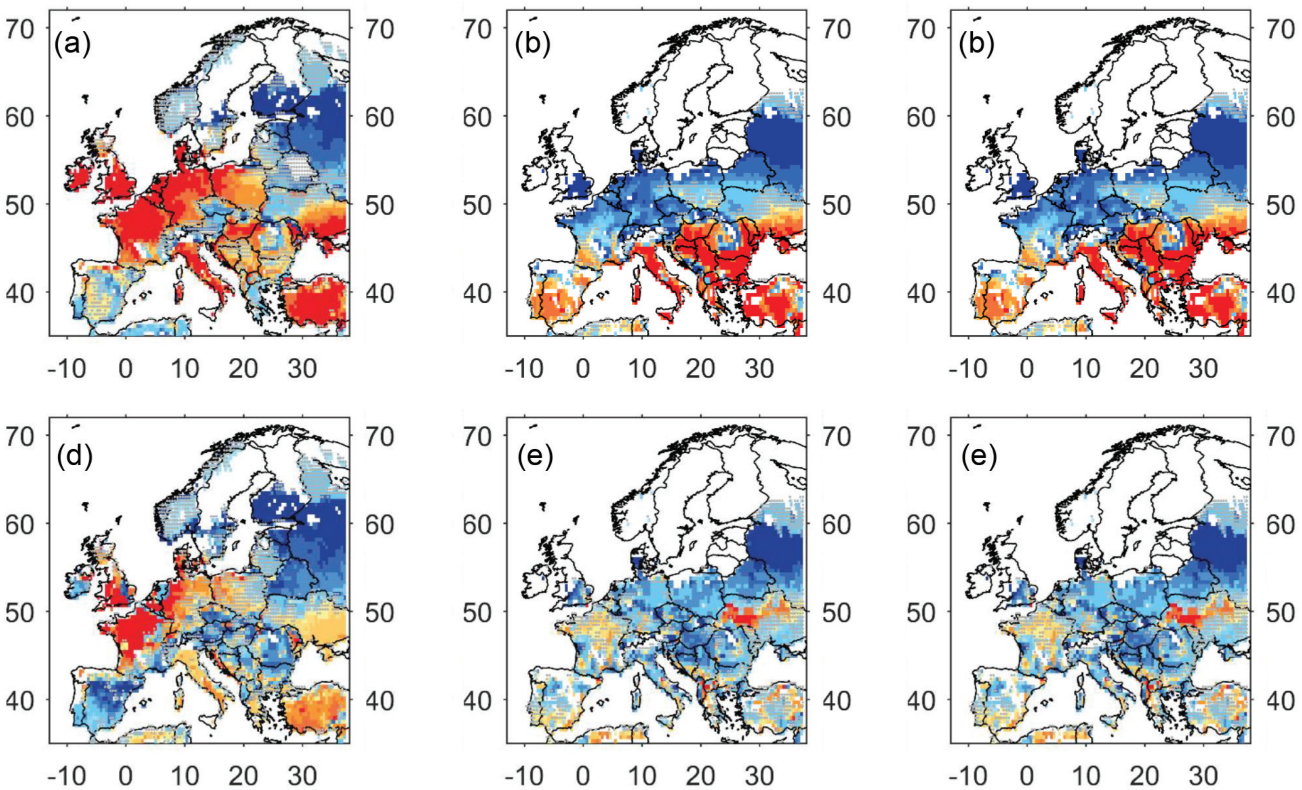


Figure 4. Projected percentage of years for which crop yield is below historical average at 4°C global warming, from HELIX. (a) Irrigated wheat; (b) irrigated maize; (c) irrigated soybean; (d) rainfed wheat; (e) rainfed maize; (f) rainfed soybean. Colours show the average from 5 simulations with one crop model driven by 5 regional climate models. Grey shows where less than 4 of the 5 projections disagree on the sign of the change.

- innovation (influencing agricultural productivity);
- climate change (influencing productivity, irrigation availability and profitability).

The European agricultural sector will respond to these future changes by changing agricultural management practices (e.g. different crops or management intensities) and/or land-use (through e.g. agricultural conversion, expansion or abandonment) to meet required levels of production and food security. IMPRESSIONS modelling suggests that Europe will be able to meet its net food demand in most scenarios, except the SSP1 / We Are The World future, where reduced agricultural productivity and increasing population and affluence lead to an excessive need for expansion of the European agricultural area to meet food demand.

3. How might land-use change to meet this?

European land-use appears more sensitive to future socio-economic change than climate change. The significance of the socio-economic factors, acting through food demand, food imports and agricultural productivity, are evident within the modelling, when comparing the European outcomes from high-end climate-only scenarios with scenario outcomes from combined climate and socio-economic change scenarios (Figure 5).

The spatial distribution of impacts on arable and livestock systems will depend on the relative impacts of future change on agricultural and forest profitability (locally and regionally) and the availability of irrigation water. Agriculture is most likely to expand northwards and westwards as climatic conditions increase agricultural land suitability, leading to relative improved profitability. Agricultural expansion in the Mediterranean region will be limited by the generally lower levels of productivity and water resources. Policy support will be increasingly important to maintain rural agricultural employment in southern Europe as increasing water scarcity and decreasing land suitability impact production and profitability.

Autonomous adaptation is likely to see northwards and north-westwards shifts in agricultural systems as land suitability and productivity change. IMPRESSIONS models suggest that trading patterns and the willingness of land managers to adopt novel land-uses play a central role in allowing efficient adaptation to changing climatic or socio-economic conditions. Therefore, these non-climatic factors will substantially determine both food supply levels and the scope for maintaining other necessary or desired land-uses in Europe under high-end climate change.

4. How might European livestock farming be affected under high-end scenarios?

High-end climate will pose important challenges and opportunities for the livestock sector in Europe. It will influence animal health and welfare issues through to the availability and quality of grassland and fodder crops and ultimately to costs and profitability. High-end scenarios are likely to lead to a reduction in cold-related stresses on production, a longer growing season, particularly in northern marginal areas and an increase in fodder maize production (due to its higher tolerance of drier conditions than grass). There are likely to be movements in the livestock industry as some production migrates to where livestock and poultry feeds are plentiful to minimise costs. Modelling suggests that grassland systems will remain throughout most of Europe, but with movement towards the more temperate north / north-west regions of Europe (Figure 5).

Heat stress is likely to increase in indoor and outdoor livestock and poultry (and during transportation). This will lead to reduced milk yields, egg production and weight gain unless adaptations are introduced, such as forced ventilation, installation of cooling pads, increased shading.

What are the main cross-sectoral impacts or conflicts?

In an uncertain future, threats to European food security may lead to regional agricultural inten-

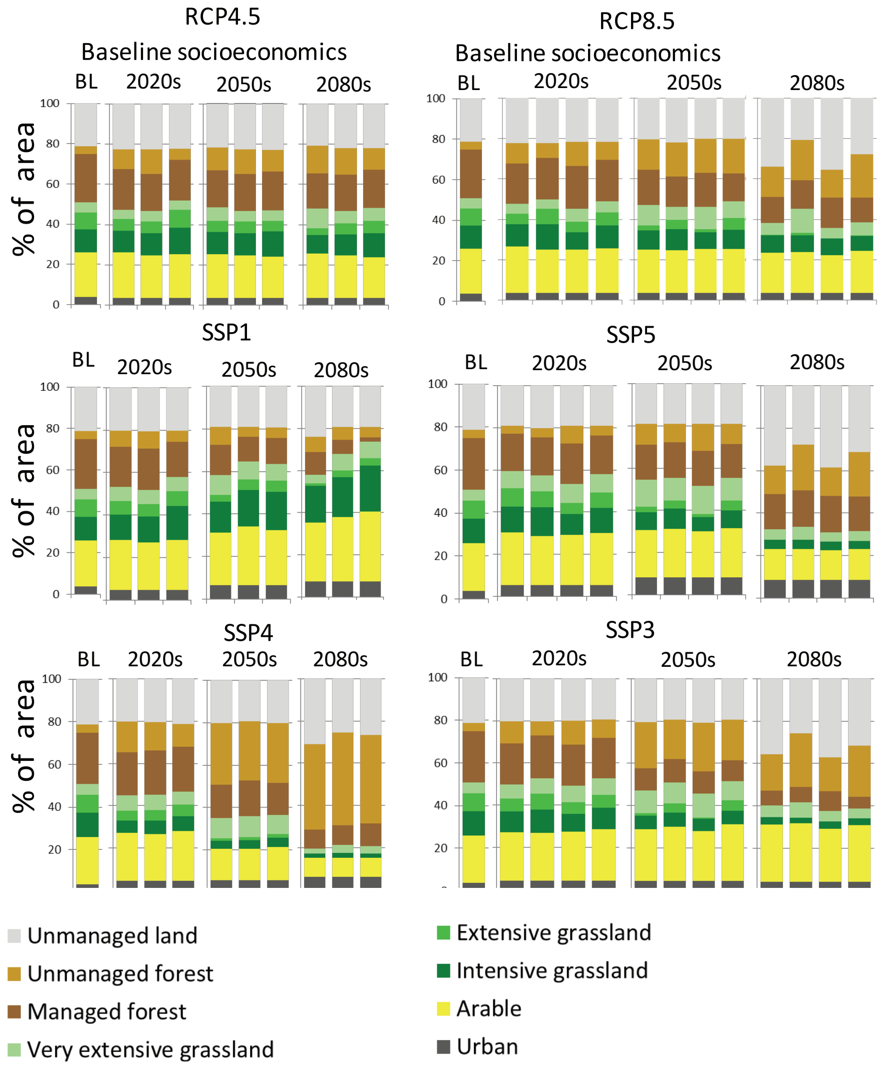


Figure 5. Simulated European land-use under a range of high-end scenarios using the IMPRESSIONS integrated assessment platform for multiple GCM-RCM combinations.

sification and/or expansion as food production is prioritised over other land-uses (forestry, biodiversity).

1. Impacts on water resources

Increasing water stress in many catchments arising from reduced water availability due to climate change and/or increasing water demand (from agriculture, public water supply and the environment) will lead to increased competition for water. Moves to water prices that reflect cost recovery may lead to increased specialisation within the irrigated agricultural sector and reduced usage of low value crops. Increased extreme precipitation events and wetter winters are likely to increase soil erosion and the transport of associated pollutants (pesticides, phosphates) to water courses. The RISES-AM case study of the Ebro Delta rice fields has shown that the main impact of sea-level rise will be salt intrusion through the subsoil, rather than direct flooding, due to the existence of coastal defences or future construction to adapt to this situation. High-end scenarios will cause increased soil salinity in most of the delta surface which will trigger a decrease in rice production (Genua et al. 2016). These findings are relevant for other low-lying rice production areas, such as the Rhone Delta (France) and Po Delta (Italy).

2. Impacts on biodiversity

Many species and habitats will be directly or indirectly (positively and negatively) affected by high-end scenarios. Modelling shows that arable field margin and forest species (Figure 6) can expect significant changes in suitable habitat provision under high-end climate scenarios. For arable species much of southern Europe will decrease in suitability, whilst some areas of northern Europe (e.g. southern Sweden) may become more suitable. Similar patterns are shown for forest species, where southern Sweden and Finland become more suitable, whilst mainland Europe, particularly in the south, Poland and the UK become considerably less suitable. Scenarios leading to regional agricultural expansion or intensification may impact natural grasslands, heaths, moors and lowland wetlands. Agent-based modelling in IMPRESSIONS suggests that intensification may result from socio-economic conditions of the kind represented by SSP1, with a consequent risk of environmental degradation. Conversely, the more challenging socio-economic conditions of SSP3 are likely to lead to widespread abandonment of agricultural land in the absence of significant

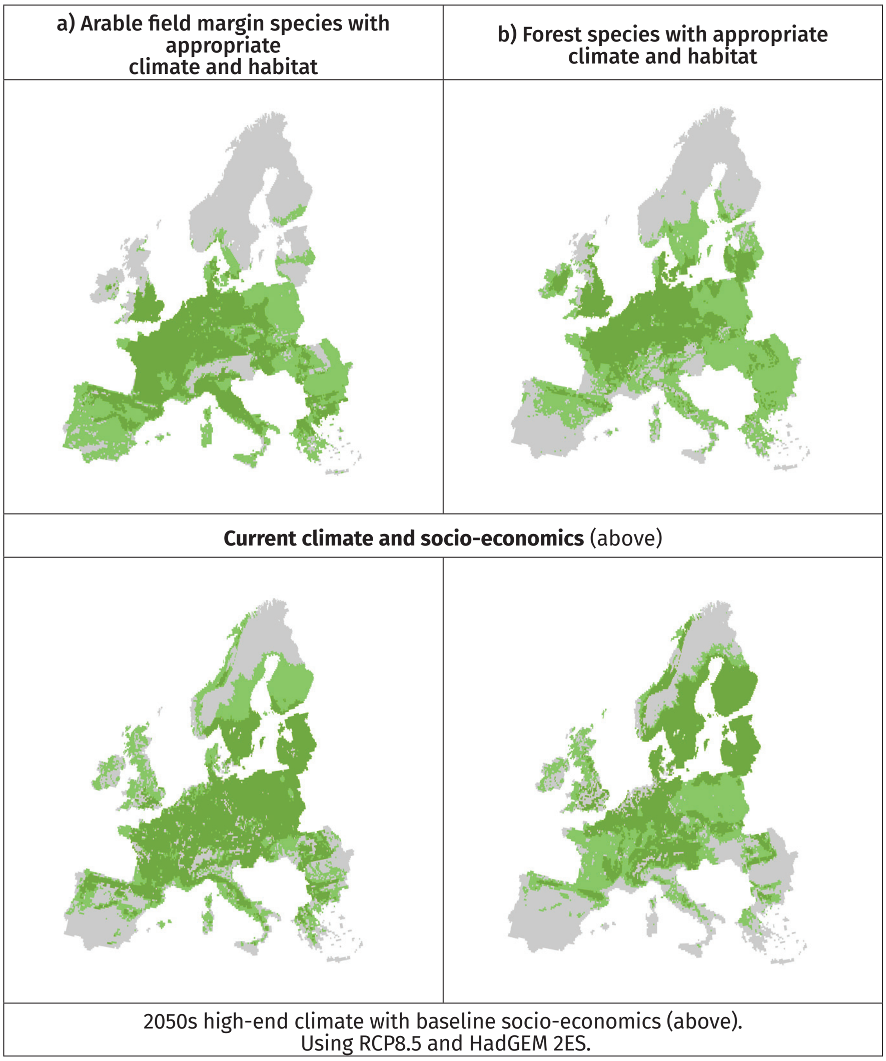


Figure 6. Shifting patterns in combined habitat and climate suitability for selected arable and forest species, from IMPRESSIONS. There are 18 arable species and 24 forest species. Grey – suitable for <5 species; green suitable for 5-15 species; dark green suitable for >15 species

production subsidies, with serious implications for farmland species, but potential benefits for biodiversity in unmanaged areas.

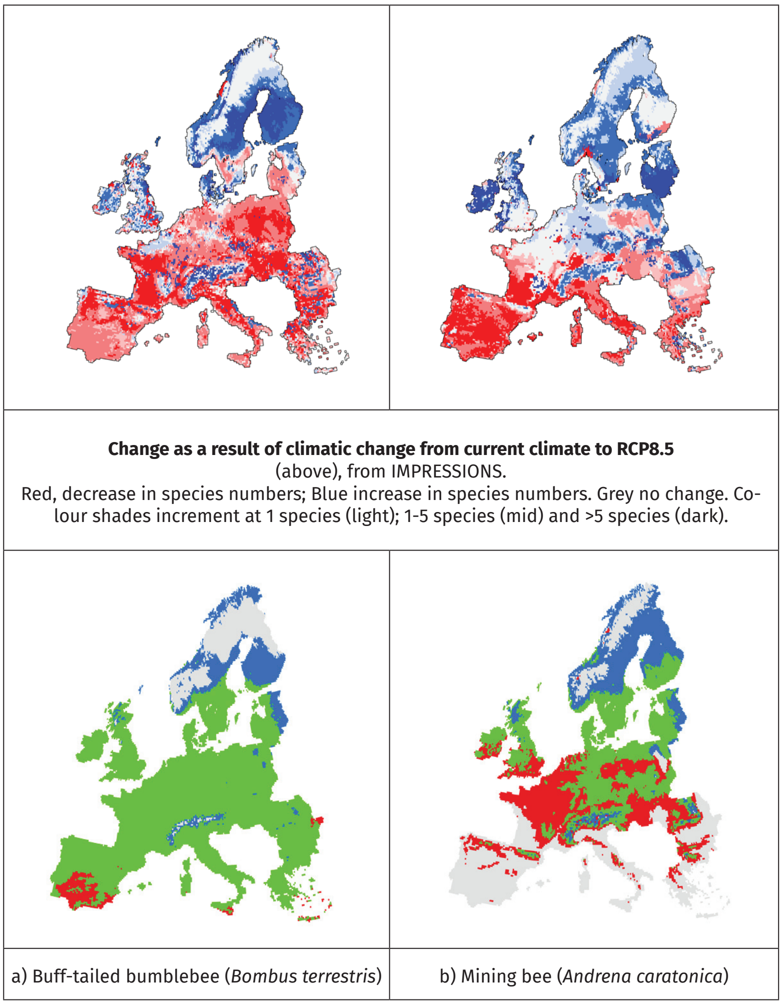
Integrated modelling studies in IMPRESSIONS show that agricultural adaptation can play a significant role in modifying the impacts, through modifying land-use change and increasing habitat connectivity to provide greater opportunities for species to adapt naturally.

3. How resilient are pollinating agents to high-end climate change in Europe?

Some pollinators, critical for producing good crop yields, may lose climate space especially in southern Europe. Modelling suggests that eight of the 10 modelled key crop pollinator species are projected to lose suitable climate space in the Mediterranean region and, in some cases, along the western coast of France, southern Britain and Ireland and Central Europe (Figure 7). This modelling does not take into account CO_2 effects on the species, or changes in lifecycle timings, dispersal or host plants. The pollination service they provide could be at risk unless other (not modelled) species are more resilient or new pollinator species become available. Conversely, projected expanded areas of cropping in southern Scandinavia are unlikely to be limited by the availability of pollinators providing that the pollinator species are able to adapt by moving with the climate.

4. What are the potential conflicts between food production and land-use for climate mitigation to avoid high-end climate change?

Conflicts can occur between food production and land-use for climate mitigation. IMPRESSIONS socio-economic scenarios include increased bioenergy production from intensively farmed land and this is at the expense of food production. If bioenergy demands were to be met from other sources, such as forests, then similar conflicts could occur, but in this case with timber production and/or carbon sequestration. However, in IMPRESSIONS, most socio-economic futures lead to land-use change being associated with increased climate mitigation (Figure 4). Reductions in the agricultural area allow the natural establishment of woodland in these areas and a consequent increase in carbon sequestration in biomass and soils. Only SSP1 within IMPRESSIONS agent-based modelling of land-use change produces a marked decrease in overall forest extent as land is converted to agricultural use to meet demands.



Change as a result of climatic change from current climate to RCP8.5 (above), from IMPRESSIONS.
Red, decrease in species numbers; Blue increase in species numbers. Grey no change. Colour shades increment at 1 species (light); 1-5 species (mid) and >5 species (dark).

a) Buff-tailed bumblebee (*Bombus terrestris*) | b) Mining bee (*Andrena caratonica*)

Figure 7. Changes in suitable climate space for two pollinators from IMPRESSIONS. Blue = potential new suitable climate space; red = lost suitable climate space; green = overlap between current and future suitable climate space.

Freshwater

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Key messages

Annual mean runoff is generally projected to increase in northern Europe and decrease in southern Europe. In the central latitudes of Europe, there is no clear agreement between models on either increases or decreases in annual mean flows.

- In projections with a high emissions scenario, the population annually affected by river floods in Europe increases from approximately 216,000 people per year in 1976-2005 to between 500,000 and 640,000 per year around 2050, and 540,000 to 950,000 per year around 2080. The projected damage costs of river flooding increases from approximately 5.3 B€ per year in 1976-2005 to 20 to 40 B€ per year around 2050, and 30 to 100 B€ per year in 2080. Much of the uncertainty range arises due to socio-economic scenario assumptions, especially the economic damages.

- Adaptation efforts aimed at trying to avoid floods may not be effective in the long term. An alternative approach to reduce the flood risk could favour measures targeted at reducing the impacts of floods, rather than trying to avoid them.

- Drought-prone areas increase with global warming particularly in the Mediterranean region. Low flows are projected to become less extreme in northern Europe but more extreme in Southern Europe. In some cases, low flows may decrease even in areas where annual mean flows increase.

- Projected increases in the severity and duration of freshwater shortages, especially for the southern part of Europe, have several implications for agriculture, forest and ecosystems, domestic supply, power supply and tourism.

- Among the most impacted countries, there is a high model consensus that substantial areas of Spain are projected to face a large increase in the duration of extreme prolonged droughts.

Policy insights

Climate is a key driver of freshwater resources and of changes in hydrological extremes. Recent studies suggest that with increasing global warming the contrasting difference of climate change effects becomes more pronounced between northern and southern European regions. Changes in weather patterns and in the space-time distribution of water availability are likely to have direct and profound impacts on all water-related sectors, including food and agriculture, energy supply and demand, health, transportation and tourism, among others. Although socio-economic developments are likely to dominate the dynamics of water scarcity, decreasing water availability could exacerbate water stress and intensify problems of water scarcity and irrigation shortfall, particularly in the southern and south-eastern European regions, and furthermore affect cross-sectoral impacts on the water sector. Given the expected large impacts of high-end scenarios on diminishing river flows in the South of Europe, the importance to allocate environmental flows using sound technical methods is crucial to keep rivers and other aquatic ecosystems in good ecological status. Resource efficiency is very important in the context of the EU's policy recommendations of the "Blueprint to safeguard Europe's water". However, it should be noted that water savings due to higher efficiency in the absence of adequate water allocation mechanisms do not necessarily lead to decreasing water use. Another way to save freshwater is to reuse treated wastewater. Water reuse is an accepted practice in several EU Member States, and the Urban Wastewater Treatment Directive pushed Member States to reuse treated wastewater "whenever appropriate", but without setting any guidelines and legal definition of the term "appropriateness". Latest results based on CLIMSAVE/IMPRESSIONS research showed the people-based adaptation archetype as the most robust solution to adapt to climate change.

This chapter provides an overview of potential impacts of high-end climate scenarios on freshwater at the European scale through five key questions. It also includes preliminary implications of 1.5°C warming "following" the recommendations of the Paris agreement signed at the 21st Conference of the Parties (COP21).

What are the impacts of high-end scenarios compared to the "well below 2°C" Paris agreement?

Projections of the mean state runoff production under +4°C global warming for Europe, show increasing trends for north-eastern Europe and decreasing trends for south-western Europe, while there are small areas of insignificant changes (-5% to 5%) in central Europe (Figure 8). Increases in runoff are more pronounced in the Scandinavian Peninsula (mostly between +25% and +75%). For the rest of the north European region projected increases in runoff are mostly between +5% and +25%. Decreases in mean runoff (-5% to -50%) are projected for the Mediterranean and for Eastern Europe. There is strong confidence (100% model agreement) for the wetter changes in the north-east regions. However for the projected reductions in mean runoff, model agreement varies between 0% (all models agree towards a drier change) and 40% (i.e., 60% of the models show decreased runoff and 40% show a wetter response). For the lower levels of warming, there is higher uncertainty on the projected negative changes compared to +4°C of warming.

Considering lower levels of warming, the relative changes in projected runoff are milder compared to the +4°C high-end scenario. At +1.5°C, an increase of +5% to +25% in mean runoff is projected for most of the European continent. Negative changes of -5% to -25% are only encountered for small regions scattered in the south and north Iberian Peninsula, south Balkans and eastern Europe.

Besides looking at the changes in mean runoff, useful information on the future water resources' availability can be derived by examining low state runoff, here expressed as the 10th lower runoff percentile. Low state runoff can serve as an indicator of reduced freshwater availability and drought conditions' formation. Under +4°C global warming, projections of low runoff show increasing trends in north-eastern Europe (+5% to +150%) and decreasing trends for the south-western part (-5% to below -80%) (Figure 9). The model agreement for this response is stronger compared to mean state runoff. For the +2°C and +1.5°C levels of warming, lower but both positive and negative changes are projected, with similar patterns.

How might future floods of European rivers impact the society?

Under high-end climate change, projections of the 1 in 100 year flood show large uncertainty in most of central Europe, with several spots of significant increase in the flood magnitude. Significant negative changes are mainly located in southern Spain and in north-eastern Europe. Recent research in HELIX revealed further insight on the frequency of future extreme peak flows in Europe. While large uncertainty affects current estimates of the magnitude of extreme

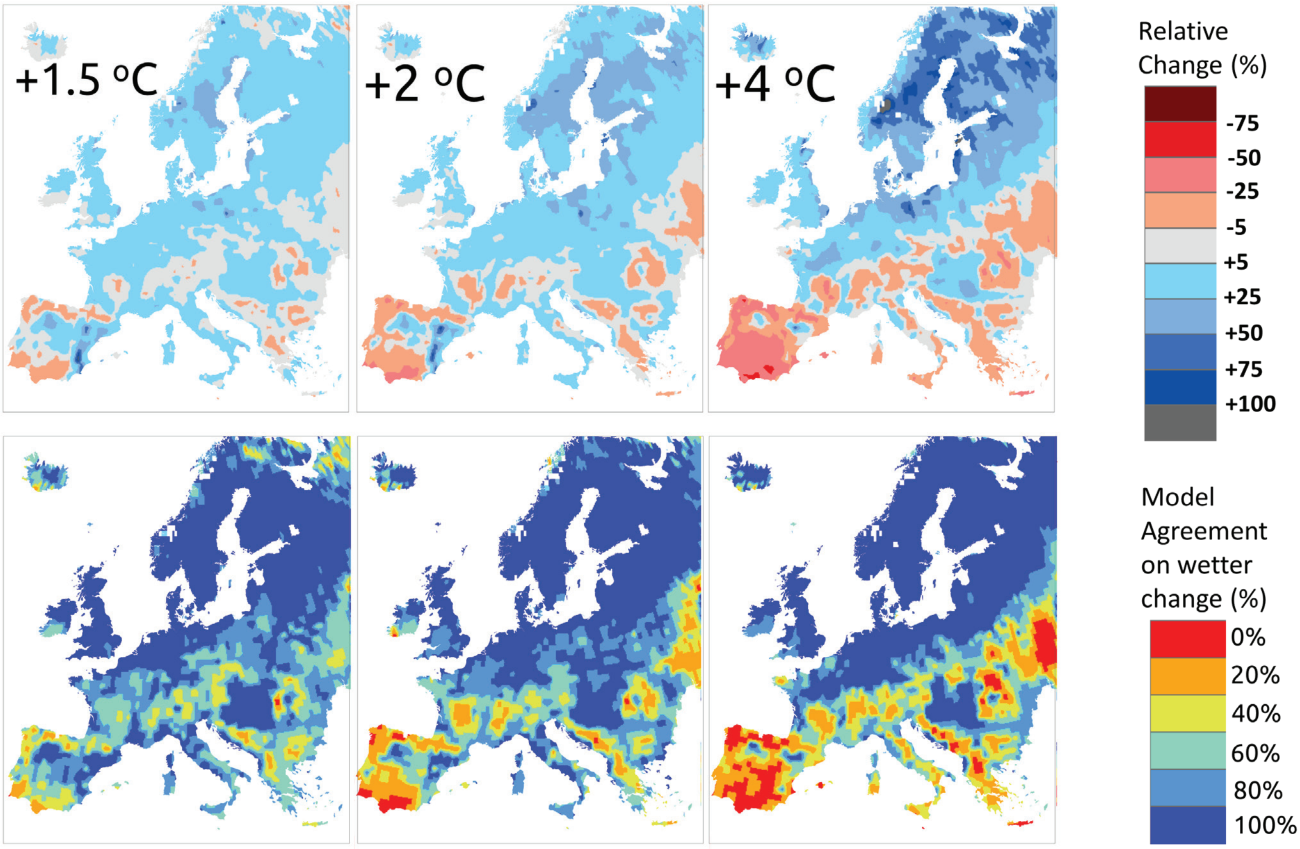

Figure 8. Changes in mean annual runoff production at different warming levels (top row) and the corresponding degree of agreement towards a wetter change (bottom row) for a set of high-resolution climate projections, from HELIX.

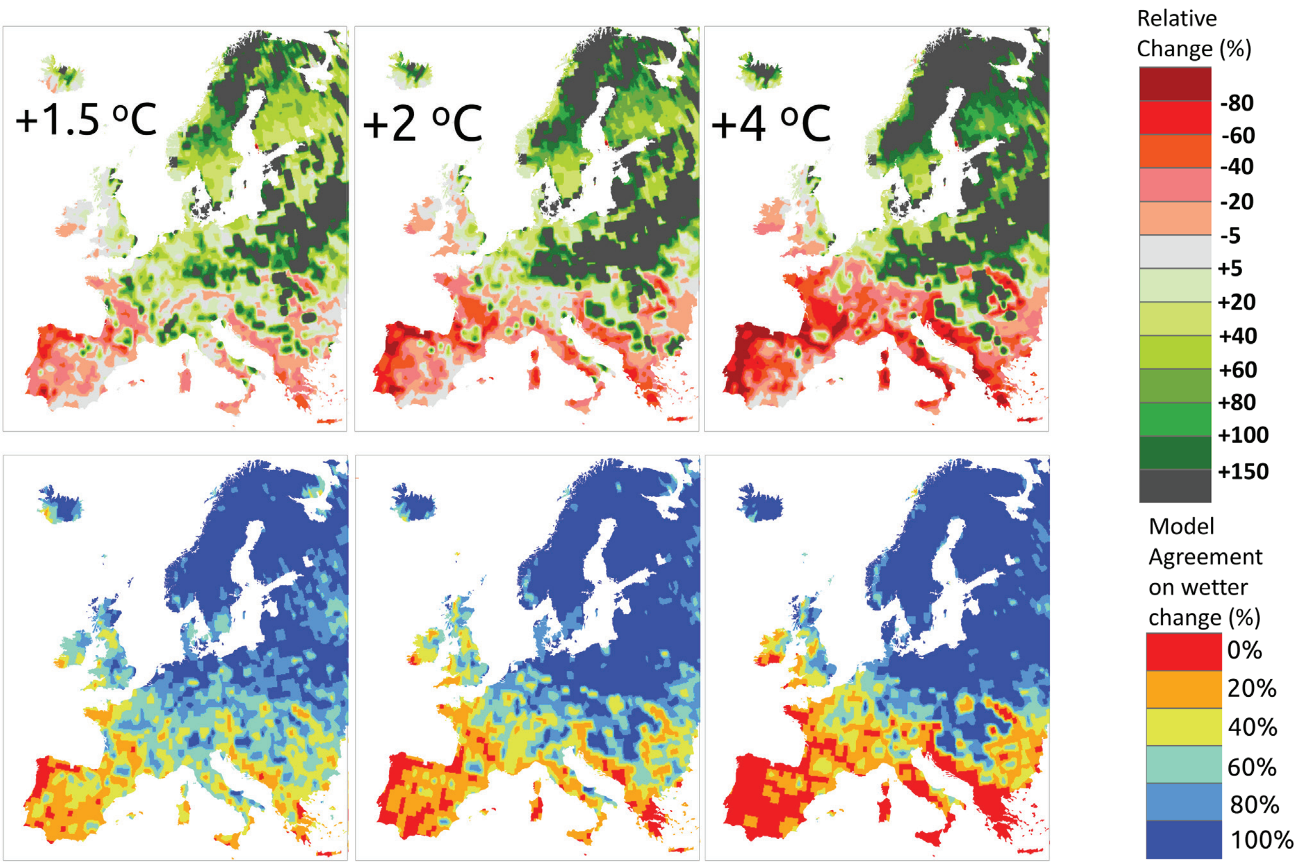

Figure 9. Relative changes in low runoff at different warming levels (top row) and the corresponding degree of agreement towards a wetter change (bottom row) for a set of high-resolution climate projections, from HELIX.

floods, their expected frequency is projected to rise significantly in most of the European countries. Projected figures show significant increase in the frequency of extreme events larger than 100% in 21 out of 37 European countries the near future (i.e., reference period 2006-2035), and a further increase subsequently.

The future flood risk in Europe can be assessed by combining the future flood hazard with spatial information on the exposure and vulnerability of population and assets. The socio-economic impact of river floods in Europe is projected to increase by an average of 220% by the end of the century, due to climate change only. By coupling such high-end climate scenarios with coherent projections of socio-economic change one obtains an overall evaluation of the future flood risk and the related uncertainty. Central estimates of population annually affected in Europe in 2050 are within 500,000 and 640,000 and within 540,000 and 950,000 in 2080. Larger variability is foreseen in the future economic growth and consequently in the expected damage of river flooding, with central estimates at 20 to 40 B€ in 2050 and 30 to 100 B€ per year in 2080 (Figure 10).

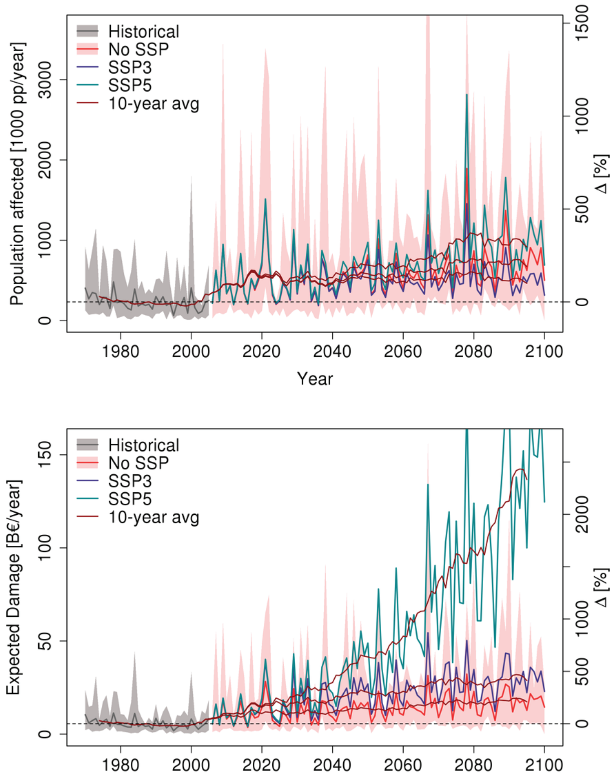

Figure 10. Historical and projected population affected (upper) and damage (lower) per year in Europe and relative change from the baseline scenario (second y-axis). Future scenarios include No SSP (only climate forcing), SSP3 and SSP5 as well as their 10-year moving average, from HELIX.

How can Europe adapt to floods and droughts under high-end climate scenarios?

Under the projected increase in the impacts of future floods and droughts in large parts of Europe, effective adaptation strategies need to be implemented to limit their impact on population and assets. The IMPRESSIONS regional Integrated Assessment Model (rIAM) at the European scale has been developed to test whether different adaptation and mitigation options reduce impacts of climate and socio-economic changes related to floods and water scarcity (but also including biodiversity, land-use diversity, land-use intensity and food provision) under high-end climate scenarios. Using this platform helps to identify a set of robust adaptation and mitigation pathways across high-end scenarios taking into consideration cross-sectoral linkages and interactions. For example, integrated water resources management can help to improve total water supply, however, climate change adaptation in regions affected by water shortages entails the need for demand management in one or more sectors and/or measures to increase water supply.

The last two decades have seen a progressive policy shift towards porgrammes to give “room for rivers”, aimed to increase the storage space of rivers by restoring floodplains and thus reducing the flood depth by spreading floodwaters over wider areas. Recent research investigated the benefits of flood adaptation measures under high-end climate scenarios in Europe. Measures include the raising of flood defences, reduction of the peak flows through water retention, reduction of vulnerability and relocation to safer areas. It suggests that the future increase in expected damage and population affected by river floods can be compensated through different configurations of adaptation measures. The adaptation efforts should favour measures targeted at reducing the impacts of floods, rather than trying to avoid them; innovative and cost-effective ecosystem-based disaster risk approaches, such as natural water retention measures (NWRM could be considered as well, including their mitigation potential. In particular, relocation (Figure 11) and vulnerability reduction measures should be further developed, thanks to their two key features of, firstly, reducing the impacts of all floods without reducing their frequency, thus strengthening the resilience of societies and ultimately the "adaptation effect". Secondly, their risk reduction potential is minimally affected by the uncertainty of climatic projections, as opposed to those measures targeted at reducing the occurrence of future flood events.

On the other hand the projected increase in severity and duration of freshwater shortages, especially for the southern part of Europe, has several implications for various sectors, including agriculture, forest and ecosystems, domestic supply, power supply and tourism. Regarding agriculture, hydrological drought can be a major stressor for this sector. For example, more frequent and prolonged droughts in combination with heat stress is estimated to be the major limiting factor in crop yields, causing increased crop stress and failure in parts of central and southern Europe, especially in the Mediterranean. Reduced summer river flow in combination with higher water temperatures is projected to affect the European power generating capacity. The overall decline in summer river flows is expected to increase the vulnerability of the power supply, calling for an urgent implementation of adaptation strategies. Hydropower is expected to "follow" projected runoff patterns with an overall increase for northern Europe and strong decline in the southern Europe.

Proposed adaptation actions include rain-water storage expansion, desalination, increased water use efficiency by water recycling and waste-water re-use, introduction of drought resistant crops and changes to the cropping calendar (for example use early ripening cultivars to escape heat or drought stress) and agriculture-based change to NWRM. Adaptation strategies for the energy sector should include a larger contribution of renewable energy resources, replacement of recirculation (tower) cooling systems and replacement of coal-, lignite- and oil-fuelled power plants by gas-fired power plants.

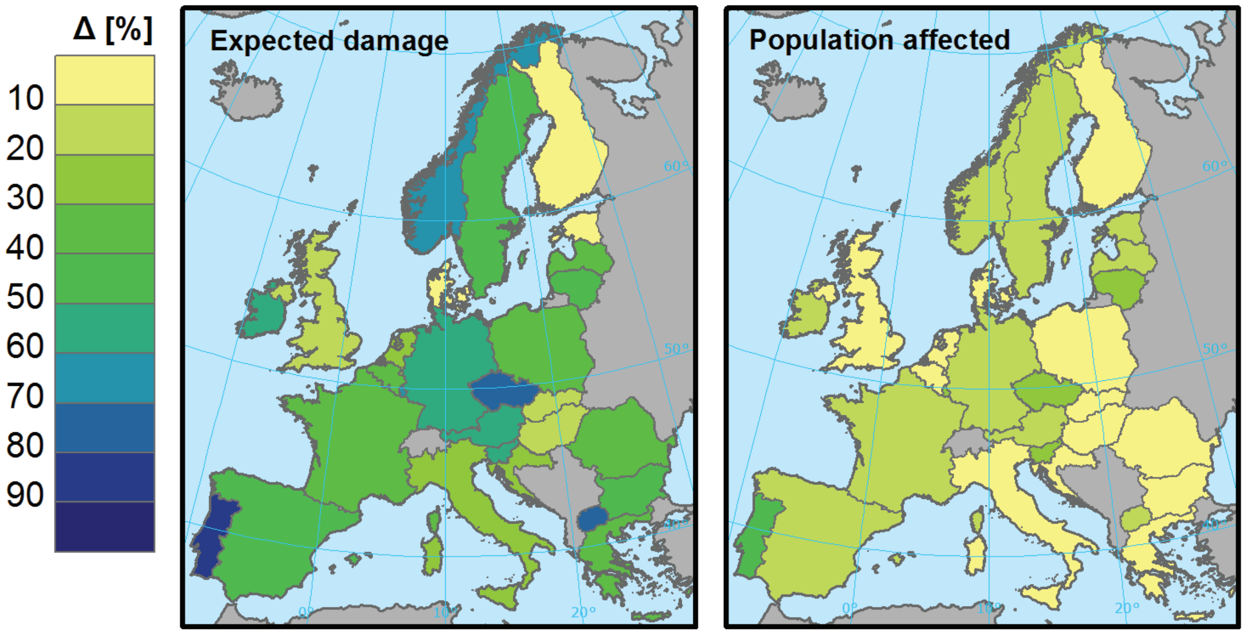

Figure 11. Average risk reduction in case of relocation of population and assets within high flood-risk areas, from HELIX.

How might mean and low flows change at the river basin scale?

Looking at the basin scale (Figure 12), mean and low flows are expected to change due to the effect of global warming. The average changes indicate an increase of mean runoff in the Ke-

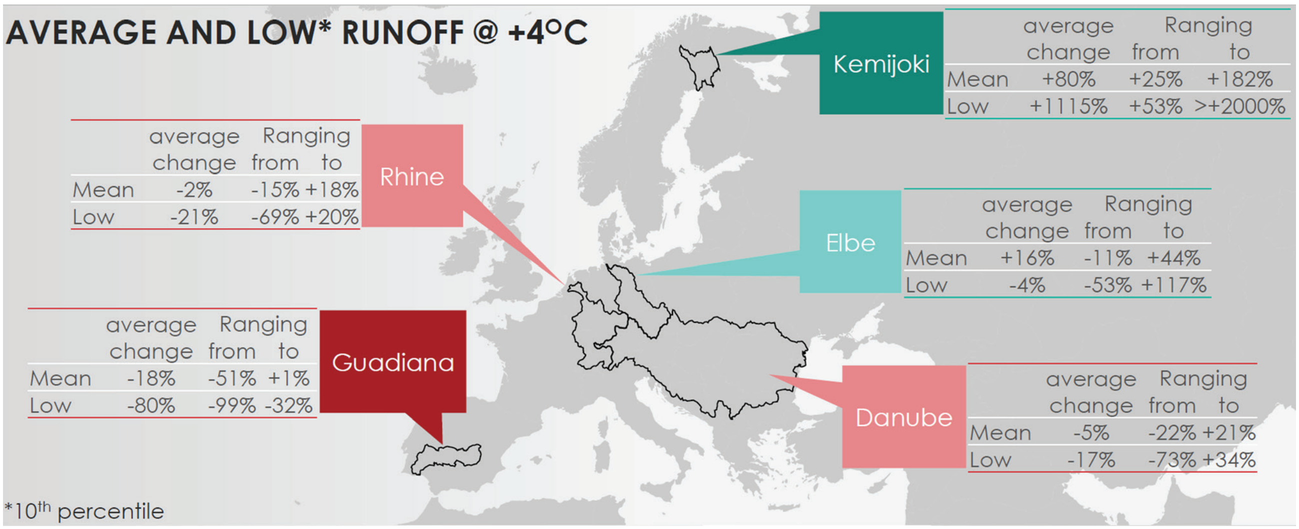

Figure 12. Relative change in annual mean and low discharge at +4°C compared to baseline (1981-2010) and multi-model range for selected river basins in Europe, from HELIX.

mijoki and Elbe basins, decreased mean runoff in Guadiana and negligible changes in the Rhine and Danube (Figure 12). For low runoff, the multi-model average suggests a positive signal in the Kemijoki, negligible change for the Elbe and signals low flow reductions for the rest of the basins. However, the range of changes projected by the different models is large and most basins span through negative and positive values, and the mean should not necessarily be treated as a robust indicator of the most likely sign of the change. This lowers the confidence in the projected signal of change for mean and low runoff at the basin scale. The unclear signal is possibly a result of two factors. The first factor is high uncertainty between the models. As central Europe is the region of higher uncertainty on mean and low runoff projections and with small average changes in mean runoff, the basins located in this part of Europe (Rhine, Elbe and Danube) show the most ambiguous mean runoff signal. The second factor is the spatial aggregation at the basin scale. This especially applies to large - transnational river basins like Danube, as their domain extends to regions of both projected increases and decreases in mean and low runoff. On the other hand, results in far northern and southern European basins (Kemijoki and Guadiana) show more robust signals of potential wetter and drier futures, respectively.

Which areas will be most drought prone?

Several southern European areas are expected to experience increases in duration of prolonged extreme droughts as illustrated in Figure 13 along with the certainty on the degree of the changes. At a world warmer by +1.5°C compared to preindustrial levels, there is low to medium certainty that small changes in drought duration (up to 10% increase) from the recent past could occur mainly in the north and south of the Iberian Peninsula. Sparse areas of similar signals are projected over north-western France and the Midi-Pyrenees, Montenegro and the largest Mediterranean island, Sardinia, Sicily, Crete and Cyprus. Under +2°C warming, the most drought prone regions are located in southern Portugal and Spain (Guadiana and Segura basins) north-western Spain, western Crete (Greece), Sicily and Sardinia. It is highly certain that Southwest Cyprus will face moderate (10-20% increase in long-term droughts. At +4°C, the duration of extreme long-term drought conditions is expected to increase covering an extensive area in the Mediterranean region. The largest and most certain increases occur at the southernmost latitudes, allowing us to identify with high certainty these areas (southern Spain, southern Italy, southern Greece and Cyprus) as the most drought prone of the European domain under high-end climate change.

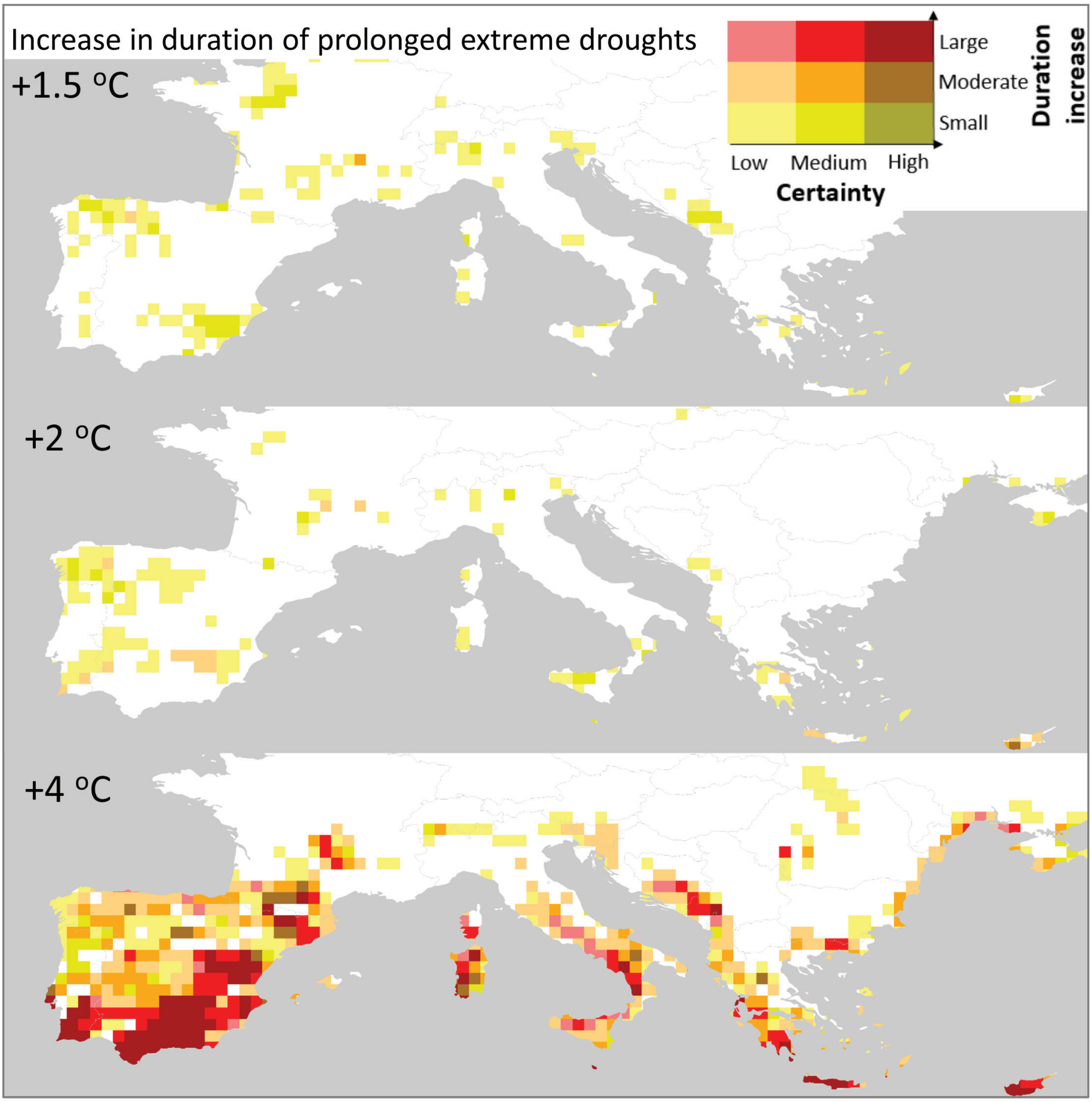

Figure 13. European areas expected to experience increases in duration of prolonged extreme droughts (48-months) along with the certainty on the degree of the changes compared to the baseline period (1981-2010), from HELIX.

Coastal protection

Lead author: Agustín Sánchez-Arcilla

Contributing authors: Sally Brown, Marjolijn Haasnoot, , Jochen Hinkel, Saiful Islam, Mustafa Mokrech, Robert J. Nicholls and Michalis Vousdoukas

Key messages

- Even if emissions and temperatures stabilise, sea-levels will continue to rise. Climate change mitigation may help to reduce the rate of sea-level rise to manageable levels, but adaptation is required to help cope with the residual rise.

- Coastal monitoring (e.g. tide gauges, beach surveys) is required to determine the environmental state, and whether acceptable thresholds of risk are being reached. This would help determine if and when adaptation needs to change in order to achieve the management goal.

- Intervention for successful adaptation will be most effective if it is bespoke, balancing financial, economical, societal, equitable, governance, legislative and environment interests. Soft engineering and nature-based solutions are increasingly encouraged for a sustainable coast, but have only been proven in a limited number of pilot cases. Further research is required into resources and effectiveness of nature-based solutions (NBS). It is recognised that not everywhere can be protected.

- Flexibility is required in adaptation, with multiple choices to achieve a management goal (e.g. defined risk levels). Adaptation pathways provide one structured way to achieve this. These can be challenging to generate due to barriers in planning for adaptation.

- Governance, societal and cultural acceptance of flexible change presents the greatest barrier for adaptation, particularly over the longer term (> 50 years). This is particularly difficult as it is hard to envisage and act on long-term change, when short-term needs are greater and more immediate than the long-term sustainability of the coast.

- Priorities will depend on policy criteria, ability to pay, societal preference and technological feasibilities. Areas with high exposure of people and assets (e.g. cities) demand more stringent protection and adaptation as risk levels are high. Lower population densities are less likely to be protected at the same level, and other adaptation options need to be explored. This will lead to equity issues, particularly if adaptation is paid from national budgets to which all citizens contribute.

Policy insights

The coastal fringe is a narrow border area between land and sea, usually considered as public domain, with management responsibilities in the hands of Member States (e.g. public domain), Regional governments (i.e. land-use planning), municipalities (e.g. local infrastructures and uses) and global level institutions (e.g. coastal sustainability worldwide). These management challenges span a wide range of sectors: environment, agriculture and fisheries, transport and tourism, with decision centres located in different departments and administrative levels.

However, many coasts around the world are facing increasing population and socio-economic activities and simultaneously a reduction of available space and resources. This reduction will be aggravated by climatic factors, such as sea-level rise, changes in storminess, which could result in flooding, erosion, saline intrusion and disruption of freshwater amongst other factors. With increasing pressures in the coastal zone, conflicts of interest in coastal use are expected to grow.

For many years there has been a wide set of national and international legislation addressing the various sectors affected by these conflicts: resources (Common Fisheries Policy and CAP); natural values (Birds and Habitat Directives, Biodiversity Strategy 2020); socio-economic values; flooding (Water Framework Directive) and integrated planning (framework for Integrated Coastal Zone Management). Sea-level rise adds additional pressures in implementing these policies.

Policy goals commonly deal with the maintenance of the coastal strip under present conditions. Future policies, including those with adaptation, need to better integrate the effects of sea-level rise into their long-term plans, but not to the detriment of short-term issues.

Are coasts vulnerable to climate change?

Due to the confluence of multiple marine, hydrological, geological and atmospheric processes, coasts experience many natural hazards, such as extreme waves, tsunamis, flooding, earthquakes, subsidence, landslides and erosion. When these coincide with low-lying land, high-density populations and industry, coasts become hazardous places unless there is sufficient protection or warning to reduce the number of people or assets exposed to hazards. Coastal hazards evolve over time. Currently sea-level rise is seen as one of the greatest risks to coastal environments threatening to increase the likelihood of flooding, salinisation and, at times, erosion (Wong et al., 2014).

From 1901 to 2010, global mean sea-level rose by 0.19±0.02m. Scientists project that this rate will accelerate due to climate change (Church et al., 2013). The Fifth Intergovernmental Panel on Climate Change report, published in 2013, well before the 2015 Paris Agreement on climate change mitigation (United Nations 2015), suggested that the likely range of global mean sea-levels could increase up to 0.98m by 2100 (with respect to 1986-2005) (Church et al., 2013). A further rise of 'several tenths of a metre' could be possible if marine-based sectors of the Antarctic ice sheet collapsed.

Early research outputs suggests that limiting global temperature rise to 1.5°C as advocated in the Paris Agreement will be challenging. Even if emission and temperatures do stabilise, sea-levels will continue to rise as oceans take a long time to respond to change. The impacts of sea-level rise cannot be entirely avoided by climate change mitigation. Therefore, planning and adapting for rising sea levels over long timescales is essential, even if there is uncertainty into the magnitude of the rise. Due to resource limitations, adaptation cannot take place everywhere, so funds need to be targeted to the most vulnerable or high-risk places.

Which coasts are vulnerable to sea-level rise?

Traditionally, low-lowing, densely populated coasts have been identified as most vulnerable to sea-level rise. In recent years, it has been recognised that a range of geomorphology, land-use and governance, and financial issues are involved in defining who or what is vulnerable. Examples of these vulnerabilities are shown in Table 1.

Vulnerability is often due to multiple causes, such as those described in Table 1, which can vary spatially and temporally. Crucially, it is often the inhabitants that define the level of vulnerability. For example, a good governance of coastal systems can lead to protection, forecasts and adaptation planning can reduce vulnerability.

Compared with some other global regions, European coasts are less vulnerable, mostly as they have a high coping capacity and coastal management measures, such as dikes, groynes, monitoring and warning systems. Although there are exceptions, countries in north-west Europe are generally more aware about the risks of sea-level rise than those in south-east

Europe. This may be because of management approaches, but also that sea-level rise is perceived as less of a threat. Over the last decade, awareness of sea-level rise and action to manage it has substantially improved throughout Europe. Elsewhere, low-lying coasts in deltas are vulnerable. For example, at least 63 million people live in the low elevation zone (land <10m in elevation and hydrologically connected to the sea) in Bangladesh (Neumann et al., 2015).

What are the impacts of sea-level rise?

Flooding, salinisation and erosion are likely to increase with sea-level rise unless adaptation is undertaken and damage costs as a result of extreme events also are likely to increase. Using the coastal impacts model, the Dynamic Interactive Vulnerability Assessment (Vafeidis et al., 2008), total sea dike and residual flood costs were projected using a rise of 0.55m, 0.74m and 0.94 in sea-levels by 2100 RCP8.5 for the 5th, 50th and 95th percentiles) and for the full range of SSPs, assuming that modelled defences are upgraded as sea-level rises and socio-economic conditions change (Figure 14).

The figure illustrates that today, total flood costs as percentage of gross domestic product (GDP), are projected to be approximately 0.02% of GDP. During the 21st century this is projected to increase fivefold to just 0.1% of GDP. Although a large increase, if no adaptation action was undertaken, total costs could be in excess of 1% of GDP by 2100. These costs are not evenly spread throughout Europe. The highest total flood costs as a percentage of GDP are projected to be in Denmark, Sweden, France and Portugal. The small island states of Malta and Cyprus are less affected by sea-level rise in terms of damage costs, but may experience wider adverse effects due to their reliance on tourism and marine activities.

What actions or policies are undertaken to reduce the impacts of sea-level rise?

Coastal engineering and softer adaptation options (e.g. laws and regulations) can help reduce the potential impacts of sea-level rise, by providing a hard defence or through encouraging building in lower risk areas. When buildings reach the end of their lives, the design of new infrastructure should consider sea-level rise. For instance, sea-level rise and associated storm surges have been taken into account in the Copenhagen Metro system, where infrastructure has been raised 0.25m above the existing level (Climate-ADAPT, 2015). However, many towns and villages remain vulnerable as they have not been planned with sea-level rise and wider coastal change in mind.

Increasingly, softer methods of protection, such as beach nourishment, are used over hard adaptation (e.g. sea walls, dikes). NBS are used too (e.g. dune building), and these are likely to become more common in the future, yet their success under the most extreme conditions are not fully known. Currently, policies of managed realignment or no active intervention (in defended areas) are less common, particularly in semi-urban areas. With sea-level rise and greater challenges in defending the coast, these practices are likely to become more common.

Inevitably, coastal protection, such as the raising of sea-walls and beach nourishment, will focus on potentially vulnerable areas which are highly threatened, such as coasts where there are high population densities and economic activities. Thus, currently, cities and large towns are highly likely to be offered protection, but many small areas of lower population or villages will remain vulnerable.

How can we plan for sea-level rise?

Sea-level rise is inevitable, but the rate of rise remains unclear. Where infrastructure has a long design life or other costly coastal investments require adaptation, this should ideally be planned decades ahead for effective planning. This means that decisions can be taken at the optimum time, so that it is effective environmentally, economically, technologically and socially. Without forward thinking, 'lock-in' to one development scenario or 'surprises' where adverse events come together could occur. Adaptation plans, therefore, need to consider short and long term issues and provide a flexible range of options.

Table 1. Different components of vulnerable coastlines. From RISES-AM. Photographs: Sally Brown, Derek Clarke

Nature of vulnerability	Geographical examples	Example
Geomorphology Low-lying (open or deltaic), small or remote islands, mangrove forest	Maldives, Mekong delta (Vietnam), Netherlands	
Land-uses Nuclear power plants, coastal roads, railways, ports	Dawlish Warren railway (UK), Sizewell nuclear power station (UK), Flamanville nuclear power plant (France), Hamburg port (Germany)	
Inhabitants Value of land, population density, governance and management, finance to protect coast	High density cities (Barcelona, Istanbul), lower density agriculture land (ubiquitous), Ganges-Brahmaputra delta (India/ Bangladesh)	

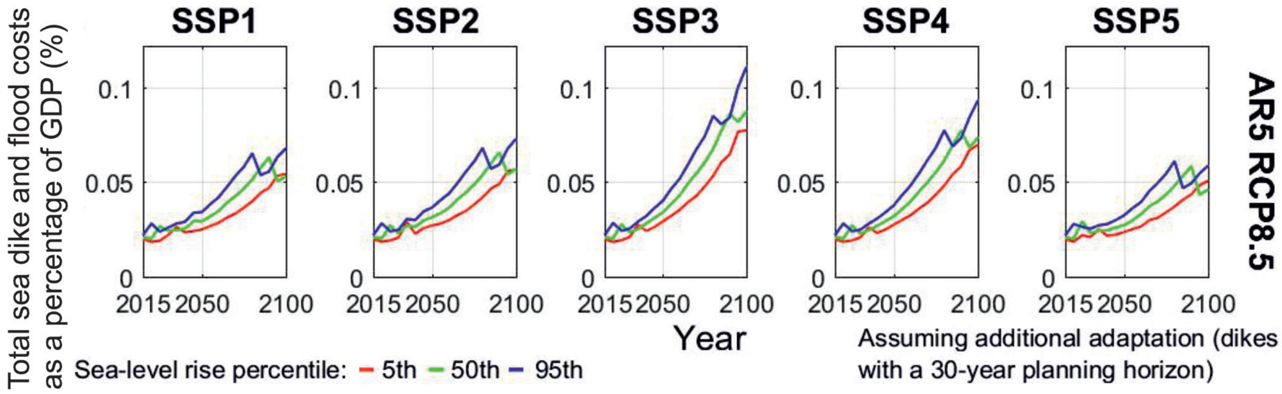

Figure 14. Total sea dike and flood costs as a percentage of GDP (%) for the European Union, from RISES-AM

One way to achieve this is through adaptation pathways – a series of sequential planning actions that lead to a low-regrets future and a defined management aim. An example of an adaptation pathway is shown in Figure 15. On the left hand side a number of adaptation options are listed. Each option has been evaluated against the magnitude of sea-level rise and time to create a pathway. Pathways are determined by adaptation tipping points, that is, where an adaptation option is no longer able to operate effectively. A change or an additional adaptation action is required to achieve management objectives.

This proactive planning is flexible over time, in response to how the future actually unfolds. By exploring different pathways and considering path-dependency of actions, an adaptive plan can be designed. An adaptation pathway can fit into a large coastal management plan, such as illustrated in Figure 16. Prior to determining the type of adaptation, the aim and objectives of the management plan are set. Potential adaptation points are explored, before an adaptation pathway is generated and detailed adaptive plans are devised to achieve this. Monitoring for potential signals that indicate when the next step of pathway could be implemented or whether reassessment of the plan is needed.

What are the barriers to future coastal adaptation and planning for sea-level rise?

In RISES-AM, technological, economic, financial and social (conflict) barriers to coastal adaptation were analysed for case studies in Croatia, Portugal, the Netherlands, the Catalan Coast (Spain), the Danube delta (Romania), the Elbe estuary (Germany), Ho Chi Min City (Vietnam), Liverpool (UK) and Hulhumalé (Maldives). The results indicated that adaptation was often technologically possible, but costly. Due to the timescale used and high up-front investments in benefit-cost analysis, only areas with very high ratios afforded protection. This was mainly found for cities and tourist areas, such as along the Catalan coast. By further integration (e.g. multiple uses of defence structures) and taking a long-term view, areas of lower population density may be able achieve more effective adaptation.

In all coastal zones, regardless of vulnerability, a major barrier was governance and social acceptability. Many stakeholders or local governments were unwilling, or unable to invest in a long-term future, as they are dealing with today's issues and finances, or are balancing conflicts of interest of stakeholders (e.g., those concerned with food security, tourism, nature protection, fisheries or shipping). Additionally, even when coastal protection is attractive in monetary terms, mobilising the financial resources for this may be challenging due to large initial investments that only have benefits over the long-term. Taken together, these findings highlight the importance of considering the equity dimension of coastal adaptation. It is likely that coastal futures will diverge with rich, urban highly engineered and protected areas on one hand, and poorer rural areas experiencing blight. This represents major policy challenges. Adaptation has to undertake wise balancing of financial, economical, societal, equitable,

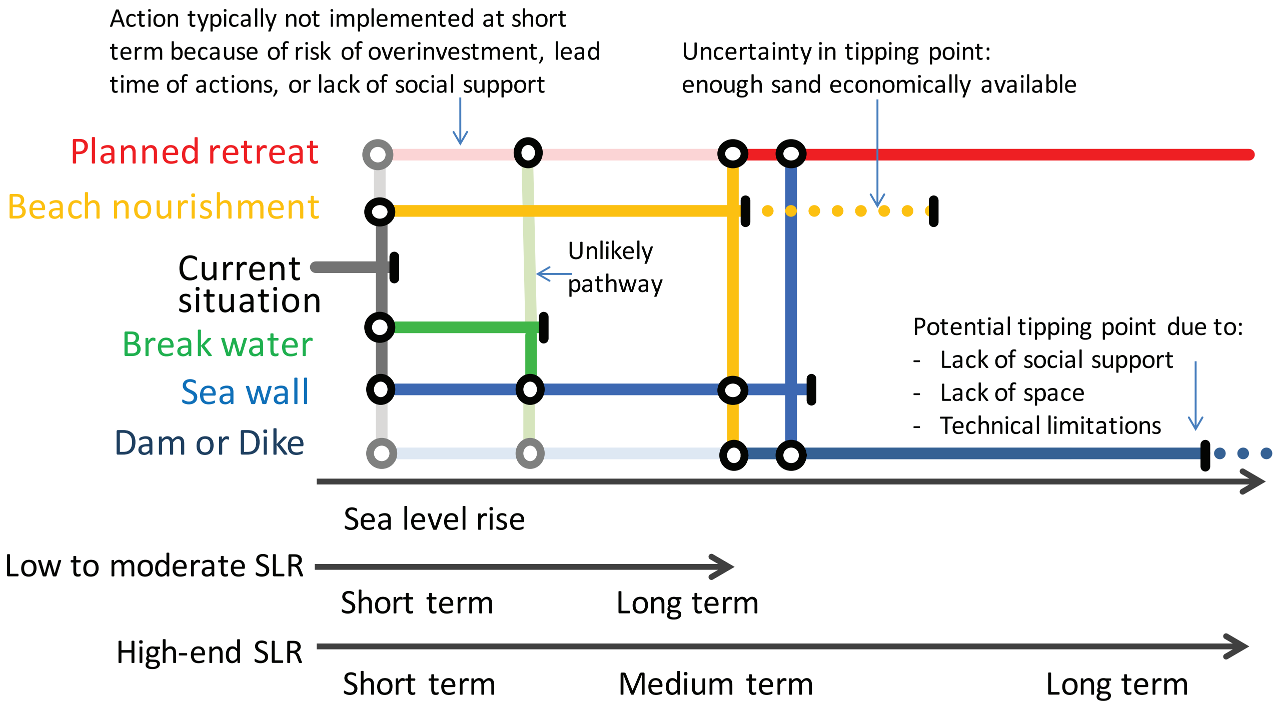

Figure 15. A stylised example of an adaptation pathways map where a set of adaptation options (listed on the left) are flexibly planned over time (each indicated by its coloured path) as conditions change and reach adaptation tipping points (white circles) (Haasnoot et al. 2013).

governance, legislative and environment interests. Furthermore, adaptation is advised to be integrated with wider coastal change, in consultation with government, non-government organisations, stakeholders and other interested parties. Addressing these issues is key in advancing adaptation. Overall, adaptation remains a matter of choice, responding to local needs, politics and finances.

What are the main research and policy needs?

Many coastal areas still need to consider how to adapt to sea-level rise. Societal change is challenging and remains a significant barrier, even to the generation of adaptation pathways. The long-term outlook of coastal protection or adaptation is also sometimes unclear. Further integrated assessments are needed, for example, of a) available resources (e.g. volume of sand or freshwater) to provide protection; b) effectiveness of the proposed interventions (e.g. limited duration nourishments) and c) equity of adaptation (e.g. in high value touristic or urban areas, compared with rural or agriculture areas).

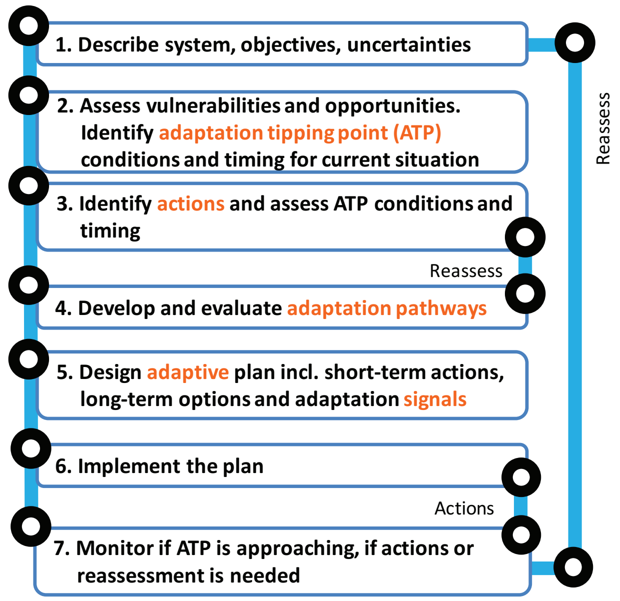

Figure 16. An example of long-term coastal planning through an adaptive plan, from RISES-AM.

Forestry

Lead Author: Harald Bugmann

Contributing authors: Richard Betts, Jinfeng Chang, Valentine Lafond and Rebecca Snell

Key messages

Some climate-induced changes in European forests are expected to occur relatively smoothly over time, whereas others may occur as "shocks", passing thresholds or tipping points.

- In climate change scenarios considered here, there is a clear north-south gradient regarding the impacts of climate change on forests, excluding other factors such as CO_2 physiological effects and nitrogen deposition. High latitudes and elevations potentially benefit from climate change, and forests at low latitudes potentially lose as a result of projected shifts towards drier conditions, particularly in the Mediterranean region. Different regional climate outcomes could result in different impacts.

- Increased CO_2 concentrations have a potentially positive effect on forest productivity. In the absence of acclimation of trees to elevated CO_2, this driver could modulate the impact of climatic change by either further increasing forest productivity (e.g., at high latitudes or elevations), or at least partly compensating for negative climatic effects.

- Forestry can be adapted to the changing climate by switching to climatically better adapted species, and moving towards forestry systems that include more than one tree species at the stand scale.

- European forests and forest products are significant contributors to the European greenhouse gas balance, constituting a major carbon sink that can help to reach EU climate targets.

Policy context

To date, there is no formal EU Forest Policy, but since 1998 has been an EU Forest Strategy (FS) and Forest Action Plan (FAP), the most recent concerning the period 2007-2011. The need for a new FS has long been recognized, as environmental and political circumstances have changed considerably over the past 20 years. The goals for the new FS are that it should (1) develop and implement a common vision of multifunctional and sustainable forest management in Europe; (2) define action priorities and targets; (3) link EU and Member State funding strategies and plans; (4) strengthen coherent cross-sectoral activity planning, funding and implementation; (5) establish clear mechanisms for monitoring, evaluating and reporting; and (6) revise stakeholder involvement (EU 2013).

Besides the FS and FAP, many other policies are affecting forests, including the Resource Efficiency Roadmap; the Rural Development Policy (which is providing 90% of the funding for European forestry); the Industrial Policy; the Climate and Energy Package; the Plant Health and Reproductive Materials Strategy; and the Biodiversity and Bioeconomy Strategies. Particularly relevant to EU decision-making is the plan to include emissions and removals from Land-use, Land-use Change and Forestry (LULUCF) in the EU's 2030 climate policy framework. Furthermore, elements of the Sustainable Development Goals are also relevant for European forestry, particularly SDG 15.2 to promote by 2020 the implementation of sustainable management of all types of forests.

Forests are influenced by a multitude of processes and at many different scales over long time periods, and hence management today only translates into effects after several decades. This leads to the necessity of long-term planning, taking into account future trends in environmental and societal drivers of forest dynamics, and a consideration of the societal demands for a wide range of forest ecosystem services, with considerable regional differentiation. Future drivers of forest change include increasing temperatures in cold regions; heat waves and severe droughts in warm regions; increasing frequency and severity of natural disturbances (e.g., forest fires, windstorms, pest and pathogen outbreaks); physiological effects of further increasing atmospheric CO_2 levels; nitrogen deposition; global prices for timber, pulp and bioenergy; intrinsic value of aesthetics and biodiversity; and future subsidies.

Policy insights

1. What are the major impacts on forests under high-end scenarios?

Some changes will be occurring smoothly over time, whereas others will be coming as "shocks" (thresholds, tipping points).

'Chronic', continuous changes of driving forces like climate, atmospheric CO_2 concentration or N deposition will lead to continuous changes in key forest variables such as primary productivity, and thus timber production (Figure 17), as well as many other ecosystem services such as water and air purification. Considering climate change alone (i.e., in the absence of natural disturbances, CO_2 or N fertilization effects), forest productivity is projected to decrease in many regions of Europe by 2100, on average by 1 to 4 m^3 ha^{-1} $year^{-1}$ (annual volume increment), i.e. about -10 to -50% compared to the current climate. Details depend on the nature of regional climate change, which is uncertain due to different results from different models. In the scenarios considered here, regions that consistently experience reductions in forest productivity include the drought-prone Mediterranean basin and the dry continental interior of the continent. Productivity increases of the same order of magnitude are expected where tree growth is currently limited by cold temperatures and is not expected to be limited by precipitation in the future, typically for high latitudes and high elevations. These variations will be mostly gradual (in the absence of other perturbations) but can happen more quickly and be more or less pronounced locally, depending on the region (Figure 17) and tree species (Figure 19).

These climate-driven changes are modulated by other drivers such as CO_2 fertilization, which may have a positive effect on forest productivity and could therefore increase the positive effects of climate change or partly compensate its negative effects. Yet, the relative importance of the direct effects of elevated CO_2 concentrations on vegetation productivity and biomass will depend on a number of factors, including 'climate sensitivity' (i.e., the response of the climate system to a given increase in CO_2). HELIX is investigating this by simulating large-scale vegetation responses at different levels of global warming – 1.5°C, 2°C and 4°C – reached in different climate models at different rates (Figure 18). Under climate change projections from a climate model with high climate sensitivity, such as the IPSL model, warming is faster and thus reaches a higher level for a given CO_2 concentration, compared to a low sensitivity model such as the GISS model. Under the low sensitivity scenario, global vegetation biomass increases more than under the high scenario, because CO_2 concentrations are higher for a given level of global warming (Figure 18). There is therefore considerable uncertainty associated with the simulated effects of elevated CO_2 on vegetation productivity, which is related not only to the model used but also to the maintenance of the fertilization effect over time. Vegetation may indeed acclimate to higher CO_2 concentrations, and/or other factors may become limiting (e.g., nutrients, water). Further research is needed to better understand the combined impacts of climate and elevated CO_2 on forest productivity.

In addition to these gradual effects, single extreme events (e.g., windthrow), and particularly series of such events (e.g., several drought years in a row), will trigger strong and sudden changes in both system properties (e.g., timber volume, carbon stock) and system dynamics, including

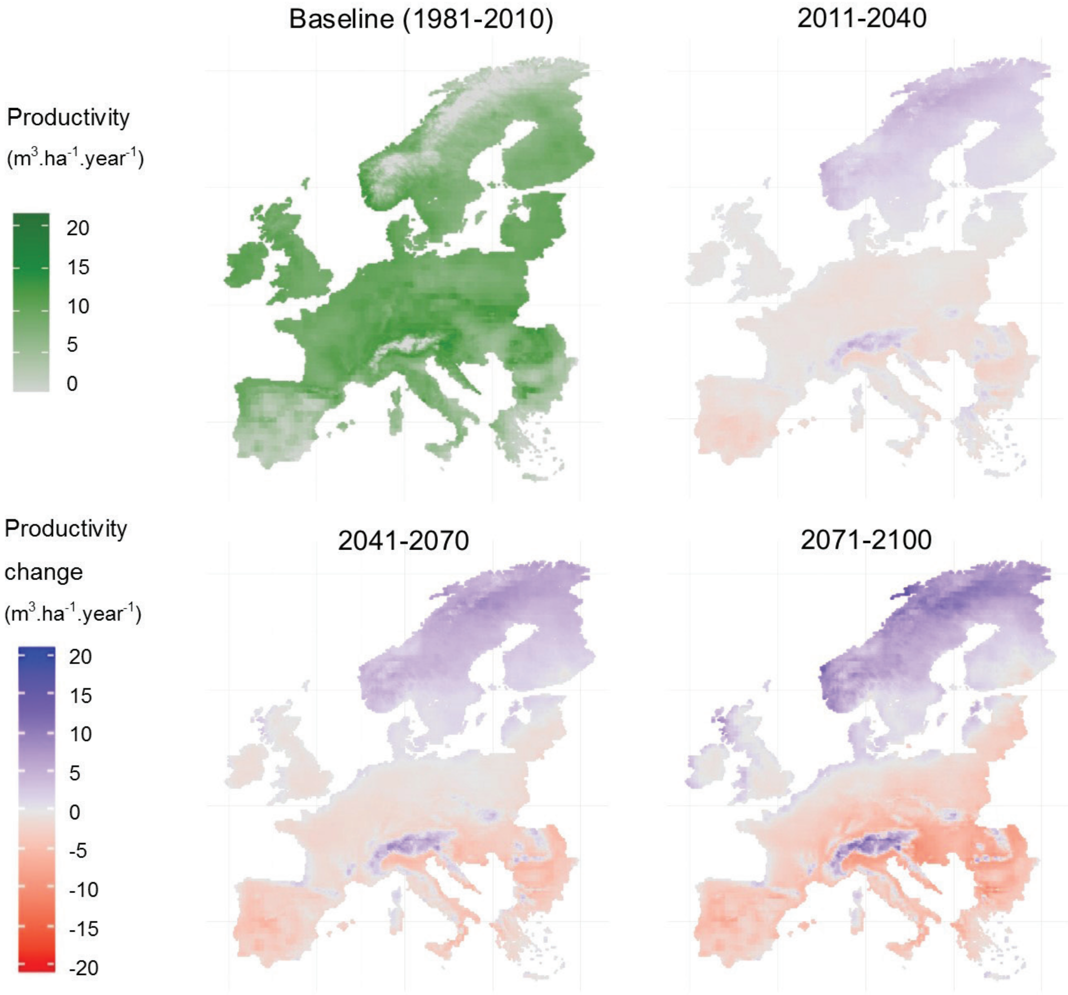

Figure 17. Productivity of Scots pine (Pinus sylvestris) under high-end climate scenarios, from IMPRESSIONS. Annual wood volume increment simulated by meta-ForClim under baseline conditions (top left, shades of green), and development under future climate change alone (productivity decreases from baseline conditions in red, increases from baseline conditions in blue). Results are averaged over three high-end climate change scenarios (RCP8.5-HadGEM2-ES/RCA4, RCP8.5-CanESM2/CanRCM4 and RCP8.5-IPSL-CM5A-MR/WRF) and assuming a mesic soil (water holding capacity of 15 cm).

the potential for widespread tree mortality induced by drought and heat waves, large changes in tree species abundance due to species-specific mortality, and forest expansion beyond current 'cold' treelines at high latitudes and high elevations induced by clusters of climatically favourable years for tree establishment. The results in Figure 17 and Figure 19 are conservative estimates of negative changes to forest productivity because they exclude such disturbances.

Changes in disturbance regimes include not only windthrow and wildfires, but also the outbreak frequency and severity of pests and diseases, such as ash wilt that is currently wiping out ash (*Fraxinus excelsior*) populations across Europe. Furthermore, novel species are likely to establish that may be disruptive to ecosystem function, such as the tree of heaven (*Ailanthus altissima*) that has been present in Europe for a long while, but now is becoming invasive in many European forests, or Japanese knotweed (*Fallopia japonica*) that is increasingly hindering forest regeneration under moist conditions across many European countries.

Thus, the many ecosystem services provided by forests will be affected strongly by these changes in driving forces, be they chronic or induced by extreme events. Whether they are beneficial or problematic must be addressed at the regional level, as the environmental impacts, as well as societal demands, vary strongly by region within Europe.

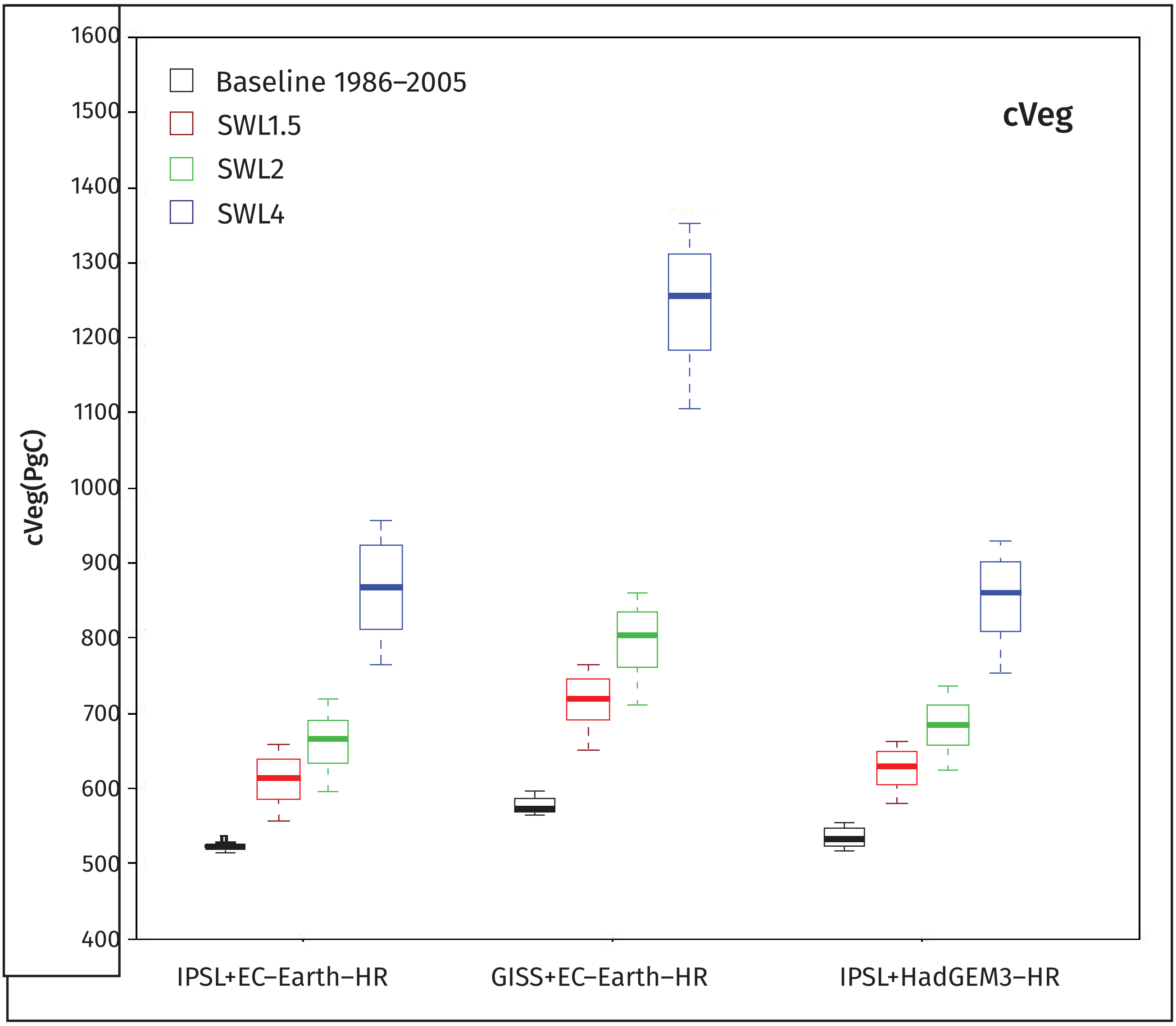

Figure 18. Changes in vegetation carbon at 3 Specific Warming Levels (SWLs) simulated by the ORCHIDEE dynamic global vegetation model driven by climate projections from different climate models, from HELIX. The centre column shows results driven by the low-sensitivity GFDL model whereas the left and right columns used the high-sensitivity IPSL model.

2. Which regions are most likely to be hardest hit by negative impacts of high-end climate change, and which regions may see a net benefit?

Under the climate change scenarios considered here, there is a clear north-south gradient regarding the impacts of climate change on forests (excluding other factors such as CO_2 physiological effects and nitrogen deposition). High latitudes and elevations potentially benefit from climate change, and forests at low latitudes (i.e., towards drier conditions, particularly in the Mediterranean region) potentially lose.

According to these simulations, forest productivity at high latitudes and high elevations is expected to increase (Figure 19), as temperature limitations on growth will be alleviated, whereas precipitation will stay high enough to maintain beneficial levels of soil moisture in spite of projected decreases in summer precipitation. Thus, either extant tree species will become more productive (e.g. Scots pine, Figures 17 and 19; Norway spruce, Figures 17 and 19), or it will be possible to use tree species that have higher economic value than those being used today but cannot be grown under current conditions (e.g., Sessile oak and Holm oak, Figure 19).

In continental, as well as Mediterranean areas, lower forest productivity is projected due to higher summer temperatures and reduced

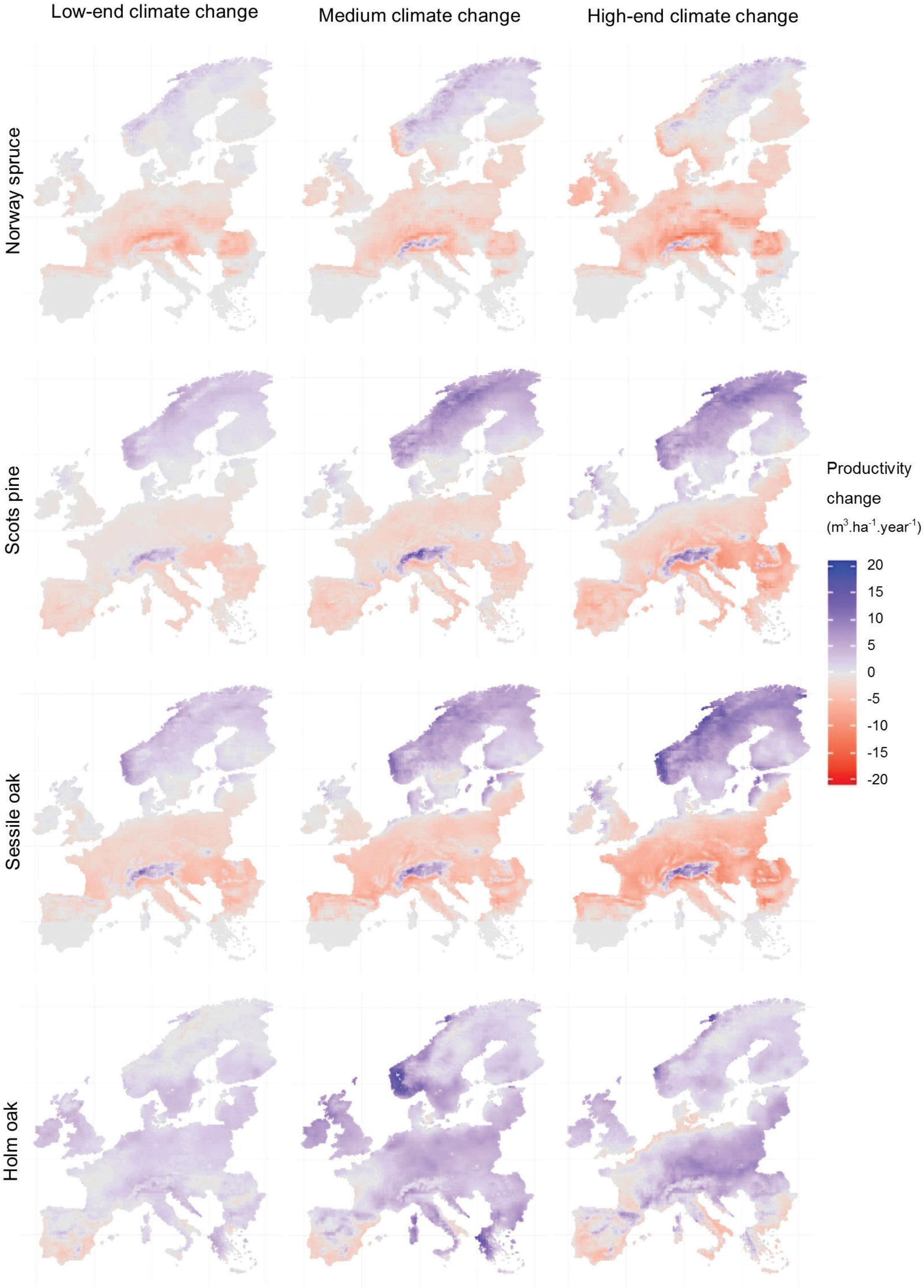

Figure 19. Projected change of productivity by 2100 under climate change for two conifer (top) and two deciduous (bottom) tree species, from IMPRESSIONS. Changes of annual volume increment projected by meta-ForClim under low-end (left), medium (centre) and high-end (right) scenarios of scenarios of HECC for the time window 2070-2100 (decreases are in red, increases in blue). Results are presented for a mesic soil (water holding capacity of 15 cm) and averaged over two or three climate change scenarios depending on the severity of projected HECC: RCP4.5-GFDL-ESM2M/RCA4 and RCP4.5-MPI-ESM-LR/CCLM4 for low-end; RCP8.5-GFDL-ESM2M/RCA4 and RCP4.5-HadGEM2-ES/RCA4 for medium; RCP8.5-HadGEM2-ES/RCA4, RCP8.5-CanESM2/CanRCM4 and RCP8.5-IPSL-CM5A-MR/WRF for high-end.

summer precipitation. These climate changes will cause increased tree heat stress and transpiration, and lead to drier soils and increased frequency and severity of drought events. This is not only expected to lead to a decrease in forest productivity (e.g., Scots pine, Figure 17; Norway spruce and Sessile oak, Figure 19), but it also has the potential to induce large-scale forest dieback, as evidenced in many regions worldwide over the past 15+ years already.

Some tree species will be less sensitive to future climate change (Figure 19). Although Mediterranean tree species are projected to be negatively affected by extreme drought events in the most southern parts of Europe, their growth is likely to remain constant or even increase elsewhere. This is the case for Holm oak, for example, whose northern expansion along the Atlantic coast of France is already being reported.

These results (Figure 19) may look different, particularly at the regional scale, if different climate scenarios were used. However, the range of scenarios spanned is quite large, ranging from very mild +1.5°C to true "high-end" scenarios (Figure 19). Thus, the range of possible forest responses should be captured well by these simulations.

3. What are the major needs for adaptation of forestry to changing driving forces?

Forestry can be adapted to the changing climate by switching to climatically better adapted species, and moving towards forestry systems that include more than one species at the stand scale.

Given the large magnitude of high-end climate change, some tree species will clearly be outside their environmental niche in many places where they are productive today, such as European beech and Norway spruce. Thus, a change in tree species is needed. The timing of such switches needs to be considered carefully, due to the long production periods in forestry. On the one hand, forest managers must not wait until the first negative impacts are evident, as this may ruin the capital. On the other hand, immediately planting new species that could thrive under the climatic conditions of, say, 2060 or 2080 may not be possible under current climatic conditions, e.g. because of their sensitivity to frosts (e.g. Sessile oak and Holm oak at high latitudes and elevations, Figure 18) or an insufficient length of the growing season that hinders tree growth. Thus, the timing of species switches needs to be determined at the regional scale, and forest managers must take into account both the rates of anticipated future climate change and the ecological properties of extant, as well as new, tree species (so-called "trend-adaptive management"). The rates of change of the regional climate are considerably more uncertain than continental or global-scale trends, which renders climate-adaptive forest management all the more challenging.

Different tree species have widely different sensitivities to driving forces, such as frosts, heat, or drought, or natural disturbances such as fire. Due to this and the unavoidable uncertainty in regional climate projections, it is likely to be highly beneficial to move from single-species to multi-species stands, as an insurance policy against catastrophic losses of timber and ecosystem services at the stand scale. There are multiple examples demonstrating not only the feasibility of mixed stands, but also their high utility in terms of both economic revenue and ecosystem service provision. Examples include Scots pine (*Pinus sylvestris*) – Silver birch (*Betula pendula*), European Beech (*Fagus sylvatica*) – Norway spruce (*Picea abies*) or Norway spruce – Silver fir (*Abies alba*) stands.

4. What is the climate mitigation potential of European forests?

European forests and forest products are significant contributors to the European greenhouse gas balance, constituting a major carbon sink that can help to reach EU climate targets.

Forests play an important role in the greenhouse gas balance of Europe, as forests and their products constitute a carbon pool that continues to increase, thus providing a net sink and helping to mitigate EU carbon emissions.

EU forests and the forest sector currently produce an overall climate mitigation impact that amounts to about 13% of the total EU emissions. Thus, they are a contributor to achieving climate targets, particularly the goal of limiting the global average temperature increase to less than 2°C above the pre-industrial level, although forests and their products alone are certainly insufficient for reaching such goals.

Forest products are also contributing to the bioenergy goals of the EU, as all wood products can – at least in theory – be burnt at the end of their lifetime. Hence it is not only direct bioenergy harvesting from forests that is important, but also the entire value chain of forest products as building materials, furniture, etc.

The large current sink strength of European forests implies that forestry could also contribute to achieving negative emissions (i.e., taking up more carbon than is being emitted by human activities) at the EU level, and hence they should be factored into corresponding policy targets.

The future climate mitigation potential of European forests cannot currently be assessed, as this depends strongly not only on the carbon that is stored on a per area basis, but also and probably even to a larger extent on total forest area, which results from competition with other land-uses (agriculture, urban, etc.). Results on these areal changes are not available yet from the IMPRESSIONS project, but can be supplied soon. However, the Forest Information System for Europe (FISE) and the forest pattern viewer service provided by EFDAC contain projections of these changes based on earlier sources (cf. http://forest.jrc.ec.europa.eu/).

Nature conservation

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Key messages

- Under high-end climate change scenarios, the combined effects of climatic and socio-economic change pose high risks to biodiversity across Europe. There is considerable risk of major transformations of many ecosystems in southern Europe.

- The greatest scope for gains in biodiversity arises from potential land abandonment, mainly in northern Europe. The magnitude and uncertainty of climate and land-use change in parts of southern Europe, imply a need for intervention to avoid the loss of key connecting habitats and the worst possible outcomes for conservation.

- Rates of climate change under high emissions scenarios would largely be in excess of the ability of species to keep up through dispersal, although the extent to which this becomes a problem will depend on the length of time the climate continues to warm.

- Support for nature conservation at local and national scales has been demonstrated to be an important factor in maintaining the scale and connectivity of natural areas.

- Land for nature conservation fundamentally depends on food demand and the intensity of agricultural production, with intensive production allowing land-sparing for conservation, and extensive production limiting the scope for nature conservation, except through multifunctional land-uses.

- Protecting conservation areas to prevent intensification in one location may lead to knock-on effects on other habitats elsewhere, for some scenarios.

- Nature-based approaches can support transition away from non-renewable to renewable natural capital and can be associated with increased co-production and provision of ecosystem services. The widespread use of nature-based solutions provides many opportunities for synergies across policy objectives, including benefits to both climate change adaptation and mitigation. As such, nature-based solutions can enable the transition from a resource-intensive towards a more resource-efficient and sustainable growth model.

Policy context

A key aim of Article 2 of the United Nations Framework Convention on Climate Change is to limit warming so that ecosystems (and biodiversity) can adapt naturally to climate change. Realization of the risks of not meeting Article 2 led, in part, to the signing of the Paris Accords or Agreement with the goal of limiting temperature rise to < 2°C relative to pre-industrial levels. However, meeting this target could potentially jeopardize not only Article 2, but also the Aichi targets and the Sustainable Development Goals (SDGs) through poorly managed land-use change (especially bioenergy impacts on food production and biodiversity).

The EU Birds and Habitats Directives led to the establishment of the EU-wide Natura 2000 network of protected areas. The EU also has adopted the Biodiversity Strategy to 2020 "to halt the loss of biodiversity and ecosystem services in the EU by 2020"[1]. Target 11 of the strategy aims to ensure that terrestrial and inland water, and coastal and marine areas, especially areas of particular importance for biodiversity and ecosystem services "are conserved through effectively and equitably managed, ecologically representative and well-connected systems of protected areas and other effective area-based conservation measures, and integrated into the wider landscapes and seascapes"[2]. Many of the actions required to meet these targets are also consistent with ecosystem-based adaptation measures for climate change. A Green Infrastructure Strategy was adopted in 2013 to promote the deployment of green infrastructure in urban and rural areas, with the Natura 2000 network an important part of this. The development of green infrastructure will also enhance the connectivity of the Natura 2000 network and strengthen the resilience of sites, including to climate change. For marine ecosystems, the Marine Strategy Framework Directive (2008) aims "to achieve Good Environmental Status (GES) of the EU's marine waters by 2020 and to protect the resource base upon which marine-related economic and social activities depend"[3].

What are the key vulnerabilities of nature to high-end climate change (HECC) and other drivers of change?

Impacts on coastal habitats

Coastal habitats will be impacted by sea-level rise (SLR) and warming, especially if HECC leads to 1m of SLR and >2ºC warming. RISES-AM explored the impact of SLR on marsh habitat in the Ebro Delta and Elbe Estuary and on beaches at the global level, focusing on geomorphological impacts. In deltas and estuaries, SLR is more critical than in other coastal areas, since: 1) their large areas at low elevations (often 0 to 5 m) enhance the risk of flooding; 2) the loss of land elevation due to sediment compaction (subsidence) adds to the eustatic SLR; and, 3) there is a strong dependence on water and sediment inputs from river basins, whose decline, due to dams and intensive water use, leads to coastal erosion and salt stress. Coastal habitats respond to SLR through natural mechanisms, such as flooding, sedimentation and vertical accretion. Feedback between inundation depth and suspended sediment concentrations allows marshes to adjust their elevation to even a strong change in the rate of SLR, provided there is enough sediment in the system. In beach environments and barrier islands, SLR and/or the frequency and surge level of marine storms increase the frequency and intensity of overwash ensuring more deposition of sand on beach crests and back-shores. This increases the elevation of the beach and the whole beach profile migrates landward.

In IMPRESSIONS, the modelling of the potential impact of HECC on coastal habitats in Europe showed a mixed response for the 2050s. Salt marshes showed some losses, while coastal grazing marsh showed little change, with increases in intertidal flats in the Mediterranean and Baltic and decreases around the North Sea and British Isles. Minor increases in inland marsh were projected in Finland, while under the same scenario large increases were projected in Eastern Europe and with smaller amounts in Sweden, Ireland and Germany.

Impacts on terrestrial species distributions and habitat

HECC poses both direct and indirect challenges for species, influencing both the species themselves and their habitats. These habitats are also affected by societies changing priorities for land-use, which are themselves influenced by both climate and socio-economic changes. Figure 20 shows model results for the climate and

1 http://ec.europa.eu/environment/nature/biodiversity/comm2006/pdf/2020/1_EN_ACT_part1_v7%5B1%5D.pdf

2 http://www.cbd.int/sp/targets/

3 http://eur-lex.europa.eu/legal-content/EN/TXT/?uri=CELEX:32008L0056

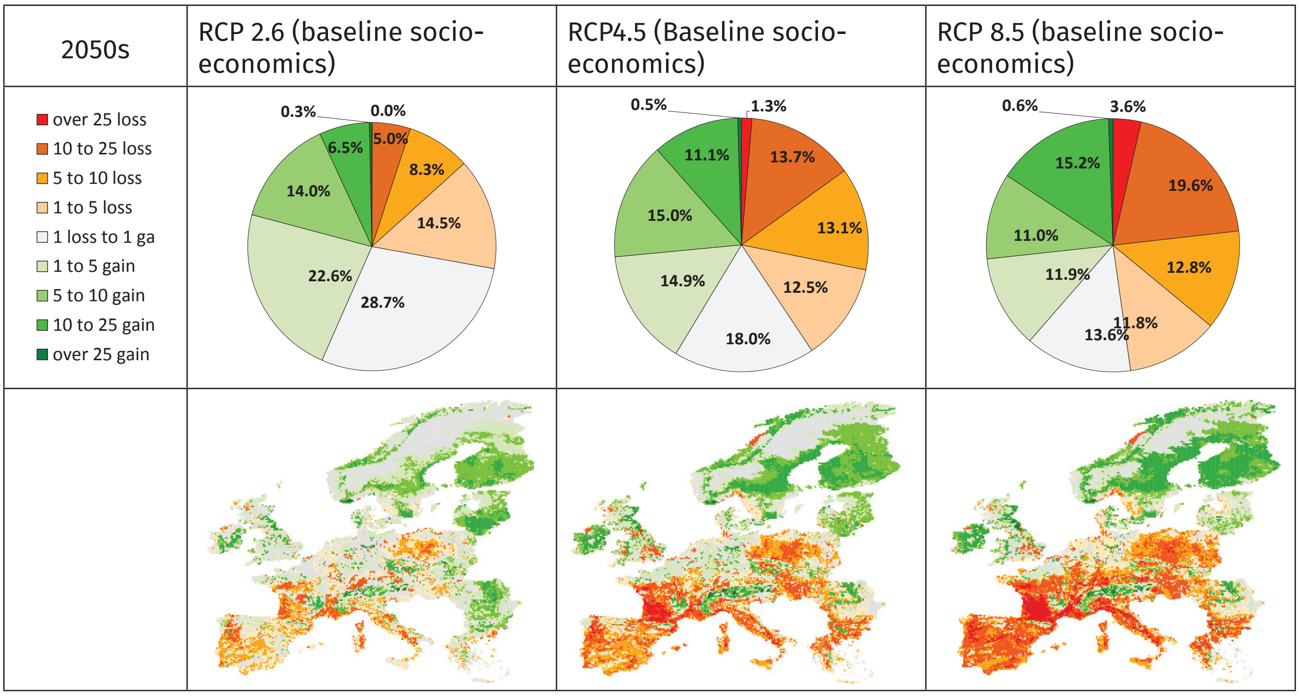

Figure 20. Change in climate and habitat suitability for 112 species under increasing levels of climate change, from IMPRESSIONS.

habitat suitability of 112 species for three RCPs with increasing levels of climatic warming. Even under low-end lower-end scenarios of HECC (RCP 2.6) 13% of Europe loses over 10 species and 28% loses more than one species. HECC leads to considerably greater impacts: more than 10 species lose lose all suitable climate space and/or habitat in 28% of European grid cells under RCP 4.5, which increases to 36% under RCP 8.5. Whilst some species may be able to adapt and gain access to new appropriate climate and habitats these are mostly in northern Europe and much of the south will see significant changes in its native biodiversity, with a potential for colonisation by some species from North Africa. Furthermore, whether species are able to access the new climate space will very much depend on the dispersal capabilities of the individual species and the availability of suitable habitats (see below).

The impact of HECC (global warming levels from +2°C to + 6.5°C) on >75,000 species of terrestrial plants, birds, mammals, reptiles and amphibians has been explored (Warren et al., 2013). The results are presented in terms of Refugia (where the climate remains suitable for >75% of the species modelled), Areas of Concern (AoC), where the climate becomes unsuitable for >75% of the species modelled), and a measure of adaptation effort (see Adaptation section).

Here, we provide preliminary results for plants and birds as these are relevant for the Habitat and Birds Directives. Figure 21 shows the number of climate models projecting a given cell to be an AoC for plant species. Even at +2°C, globally, some areas of southern Europe have a small risk of becoming unsuitable for >75% of the plants. Under HECC, the risk increases substantially in southern Europe and becomes widespread at +6°C. Thus, many parts of Europe risk becoming climatically unsuitable for a large percentage of plant species with habitats under considerable pressure to transform into different habitat types putting the work completed under the Habitats Directive at risk. Moreover, this does not account for the additional, potential risks arising from land-use change (see the section on vulnerability).

Figure 22 shows the number of climate models projecting a given cell to be an AoC for bird species. The climate remains suitable for a greater number of birds than for plants. Only under global warming of 6°C or more do large areas in southern Europe become unsuitable for greater than 75% of bird species, assuming no dispersal. However, even if the climate remains suitable for many species, habitat transformation would lead to changes in bird communities and ecosystem functioning. Even if areas do not become AoCs, Figure 23 shows that much of southern Eu-

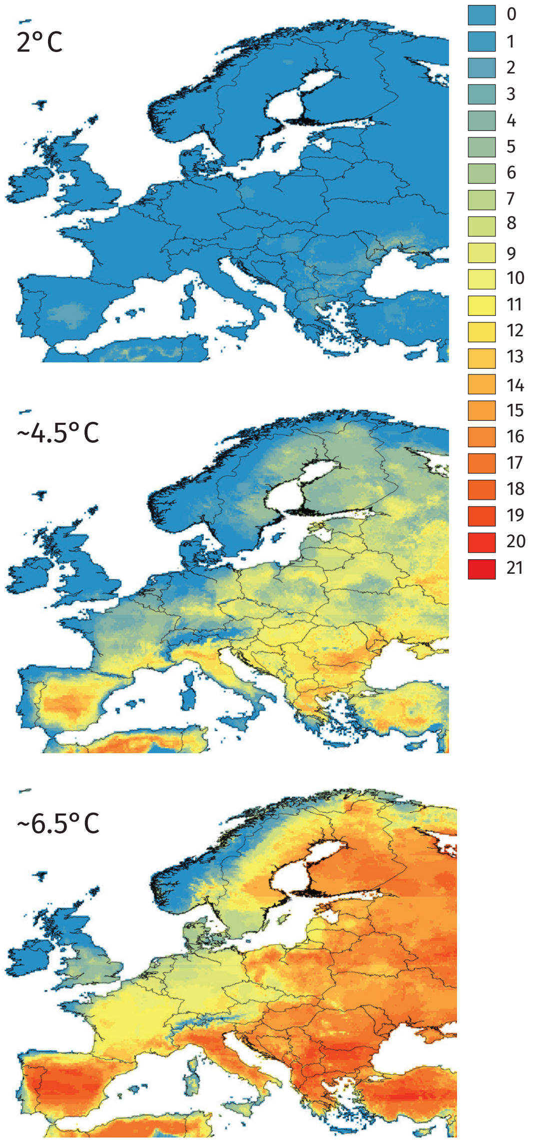

Figure 21. Plant Areas of Concern (climate becomes unsuitable for >75% of the species modelled) in Europe at 2°C, ~4.5°C, and ~6.5°C above pre-industrial (no dispersal, from HELIX).

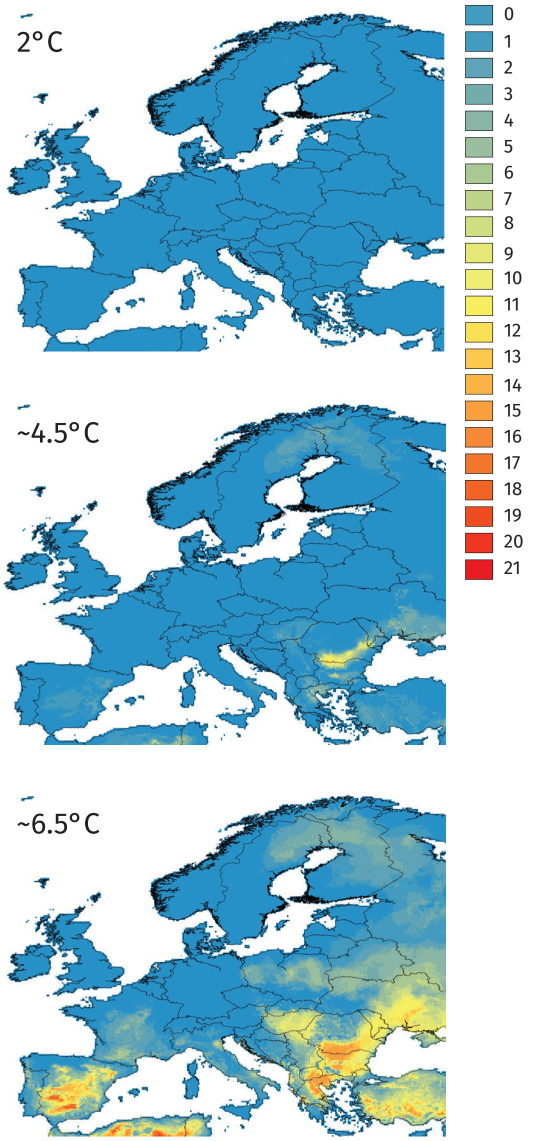

Figure 22. Bird Areas of Concern (climate becomes unsuitable for >75% of the species modelled) in Europe at 2°C, ~4.5°C, and ~6.5°C global warming above pre-industrial with no dispersal, from HELIX.

rope would cease to be a climatic refugium for birds, meaning that large areas would become climatically unsuitable for between 25% and 75% of bird species. This suggests that actions put in place under the Birds Directive would be at increasing risk with increasing temperatures. The results indicate that with increasing temperatures there is risk of major transformations of many ecosystems in southern Europe.

Adaptation opportunities

There are a number of ways in which species can adapt to climate change, but the modelling used in IMPRESSIONS and HELIX is only able to capture aspects of dispersal and connectivity. Available information from paleoecological studies shows that movement has been a common response to climatic changes in the past. While it is true that species lacking the ability to move may be able to develop other adaptive responses, such as epigenetic changes, evolution, or the expression of phenotypic plasticity, the data on climate changes and past mass-extinction events would indicate that this has not commonly occurred in the past, although there are some exceptions.

Dispersal and connectivity

The ability of species to move (disperse) in response to HECC is dependent on: 1) rates of cli-

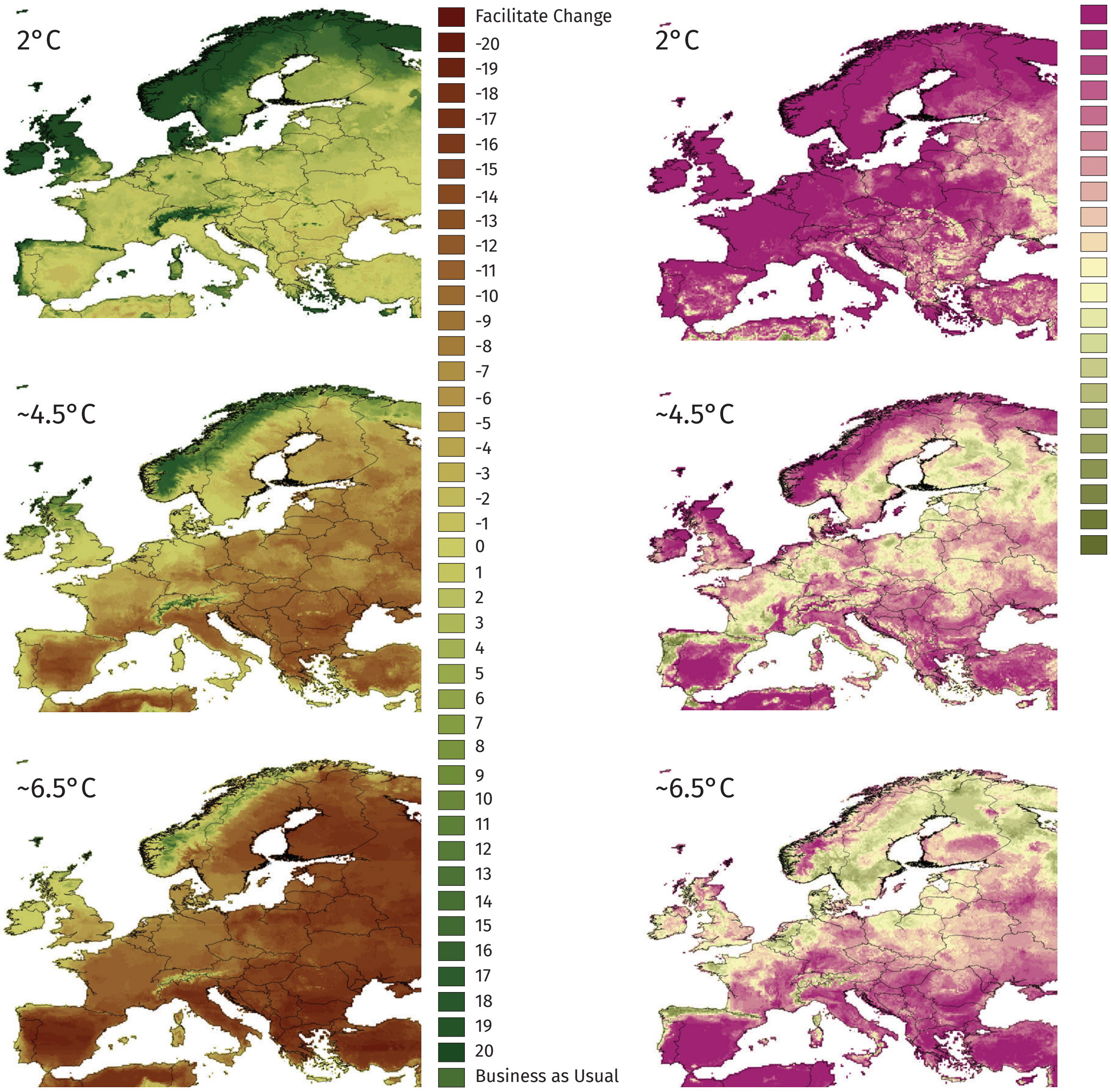

Figure 23. Maps of Adaptation Effort Indices for 2°C, ~4.5°C and ~6.5°C global warming for plants (see text for an explanation of the indices), from HELIX.

mate change relative to dispersal capability; 2) corridors or connectivity of suitable habitats and climates; and, 3) lack of barriers (fragmentation, urbanization). HECC rates will largely be in excess of the ability of species to keep up through dispersion, although whether this becomes a problem will depend on how long the climate continues to warm. If the climate stabilizes, species may be able to catch up, but this is limited by the size of the climatic range and the duration HECC. However, results suggest that the habitat changes accompanying HECC will make this difficult. Moreover, species with small climatic ranges would be at risk of extirpation since there is no remaining suitable climate space.

HELIX looked at adaptation in two ways: a) a measure of adaptation effort and b) a measure of necessary connectivity. The adaptation effort index (AEI) (Figure 23) combines the Refugia and Area of Concern Maps. The more likely an area remains a refugium, the less specific adaptation action is required. Thus, the higher the AEI the more likely that current management practices would be suitable. Regions with values of AEI between 10 and -10 are likely to require some revision to management plans. However, as AEI drops below -10, current management practices would no longer be suitable for maintaining existing habitat. It is possible that the best adaptation would be to facilitate

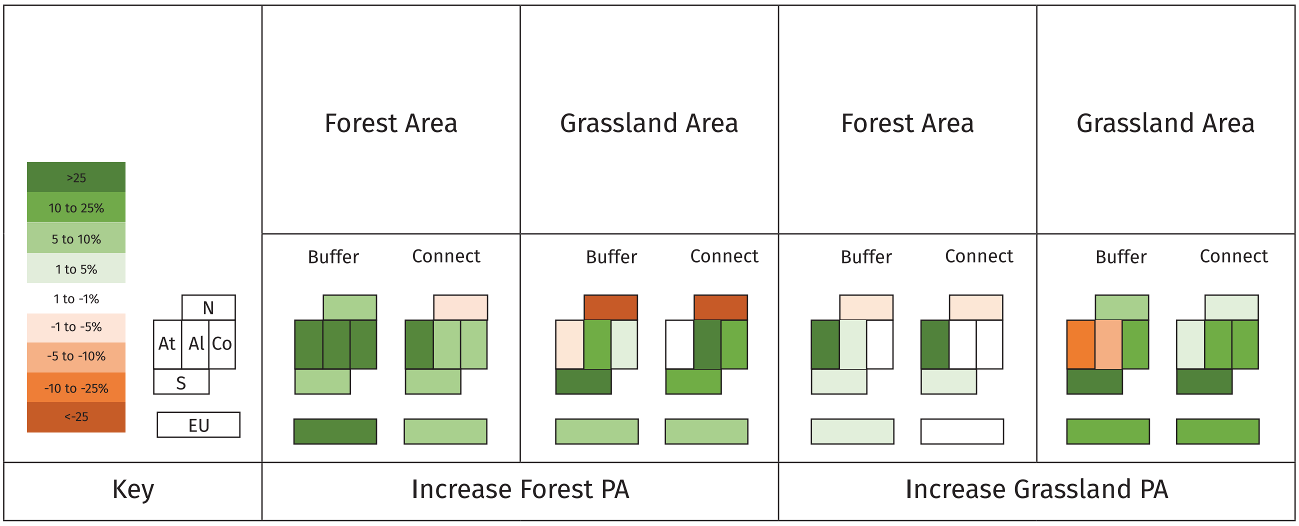

Figure 25. Regional changes in habitats resulting from changes in protected areas (up to x2 current PA), from IMPRESSIONS. Changes are relative to the future scenario (2050, CSMK3 A1 mid) with 100% current day PA. Boxes represent IPCC's five European regions. N: Northern; At: Atlantic; Al: Alpine; Co: Continental; S: Southern and EU: overall European change.

the change from one climatic type to another (for plant communities), as with plantations and 'restoration'. The Connectivity Necessity Index (CNI) (Figure 24) indicates which areas would benefit the most from habitat connectivity as an adaptation strategy. A CNI of 0 indicates no difference in status as a refugium with or without dispersal in the models. The higher the CNI the greater the difference between the number of models projecting a region would be a refugium with and without dispersal. A CNI of 21 indicates a cell would be a refugium if species could freely disperse, and would not be a refugium if they could not. With 2°C warming, there are only a few areas where connectivty makes a large difference in refugia status. With increasing temperatures, the necessity of connectivity and larger intact ecosystems increases. However, increasing temperatures are also likely to lead to greater land-use change and fragmentation. Thus, the use of connectivity as an adaptation option becomes more important, but less likely under HECC.

Protected areas

Modelling shows that increasing protected areas (PAs) can lead to significant changes in land-use, and habitat conservation. PAs are increased by preventing a habitat (e.g. extensive forest and agriculture) from being replaced by a more intensive habitat (e.g. intensive agriculture, urban). New PAs can also be created from the existing Natura2000 network by: a) buffering existing sites, e.g. protecting additional forest area by expanding the PA boundary; or, b) building connectivity, e.g. targeting cells with large forest areas that are not currently protected, thus broadening the spatial distribution of PAs and reducing inter-site distances. Figure 25 shows that both methods for land allocation (buffer/connect) lead to different regional patterns in habitat cover (%) and that regional trade-offs result from increasing PA. Protecting forests leads to a 25% decrease in extensive grassland in northern Europe as a result of shifts in the land-use system, as without PA, agriculture, rather than forestry would have occupied the areas that become protected forests in western, central and southern Europe. As a result, when forest areas in these locations are prevented from intensifying (i.e. from becoming agriculture), it is necessary to use land elsewhere to satisfy food demand. Thus, the model projects northern Europe as developing intensive agriculture in place of both forests and extensive grasslands to compensate. This is important as it shows that in some scenarios, PAs that prevent intensification and protect habitats in one location may affect other habitats elsewhere. Also, whilst protecting forests increases forest cover relative to the same scenario with no increase in PA, total forest cover decreases relative to the present by up to 30%, even when forests are protected. This is because without the species adapting to meet new climatic conditions many forest areas become climatically unsuitable leading to forest loss even within in PAs. This stresses the importance of foresight in management within PAs, and the need to consider a PA network that adapts spatially to HECC.

When expanding PAs to target extensive grassland, buffering gives a decrease in extensive farmland in Atlantic and Alpine regions and a concentration of grasslands in the southern and continental regions. This is because although the Atlantic and Alpine areas would be the most profitable in a situation without an increase in PA, when buffering is used to constrain extensive grasslands to areas surrounding existing PAs, these areas are not used and extensive grasslands cluster around existing PAs in the southern and continental regions. This means that in scenarios where buffering is used to generate bigger areas of connected habitat it could be at the expense of placing these habitats in areas with the largest economic benefits. It is important to note, however, that 'extensive grassland' reflects areas of extensive livestock farming, rather than "natural grasslands" per se and so, its allocation is driven by livestock profitability. This highlights the real-world trade-offs in terms of the regional context of conservation particularly for habitats with mixed agricultural, cultural and conservation benefits. Should we buffer and preserve large areas for habitat and cultural heritage reasons, or is it possible to recreate these conditions elsewhere, and if so can/should we prioritise agricultural production and manage land for species habitats elsewhere? Whatever the answer, for both forests and grasslands any changes in PAs will have significant land-use implications that will vary considerably by region even under relatively moderate climates.

Permeable landscapes - less intensive land-use

Permeable landscapes allow species to move across them, facilitating the colonisation of new areas, or dispersal or other behavioural movements. Permeable landscapes are often less intensively used or unmanaged areas, or have specific features to facilitate movement, such as ecological corridors. IMPRESSIONS modelling for the 2050s shows a mixed response, with areas of southern Europe and Scandinavia mostly reducing or maintaining their area of extensively farmed land, whilst increasing the area of unmanaged land. Elsewhere, there is little change, or an increase, as with unmanaged land in parts of eastern Europe. Areas of increase have the potential to improve the availability of habitat and landscape permeability particularly for endemic and non-agricultural species, facilitating adaptation. Such land-use change may, however, come at the cost of intensive farming with higher agricultural yields from more fertilizer and pesticide use that would affect agricultural species, as well as reducing water quality and climate mitigation.

Managing adaptation in coastal habitats

Natural mechanisms involved in coastal marsh resilience to SLR can be enhanced through management measures based on natural system functioning and ecological engineering (Ibáñez et al. 2014). Enhancing inorganic and organic accretion in wetlands is the main goal of adaptation management to cope with SLR. In general, the contribution of organic matter to vertical accretion is more relevant in fresher (water) habitats, so the control of marsh salinity with fresh water inputs to avoid salt intrusion due to SLR, or even to promote a change to a fresher habitat is an option under certain conditions. For inorganic accretion, the two main sources of sediment inputs are rivers and the near-shore environment. In both cases, management consists of restoring the hydrological fluxes and connectivity between the coastal wetland and the fluvial or marine systems (or both). In many cases, restoring sediment fluxes requires more 'permeable' human infrastructures such as dams, levees and dikes.

To what extent are current nature conservation policies and practices robust to HECC?

Biodiversity vulnerability and the scope for successful conservation under HECC depends on the interplay of climate and human land-use. Even if conservation is prioritised, the need for basic resources such as food, water, energy and timber means that natural areas may suffer loss of extent and coherence independently of any direct climate impacts (Heller and Zavaleta, 2009). Climatic and anthropogenic drivers are likely to work in concert because the areas most affected by climate change will require the greatest adaptations in land management, therefore generating significant disturbances to natural systems (Hansen et al., 2001; Opdam and Wascher 2004; Sutherland et al., 2009).

Understanding these drivers of change in conservation requires the integration of climatic, biophysical and land management models. Integrated simulations suggest that the combined effects of climatic and socio-economic changes make a loss of biodiversity across Europe highly likely in the future, with the greatest scope for gains arising from potential land abandonment, mainly in northern Europe (Brown et al., 2015). Conversely, the magnitude and uncertainty of climate and land-use change in parts of southern Europe implies a need for intervention to avoid the worst possible outcomes for conservation and to identify strategies to support both the human and natural systems in those areas. However, these results are based on economically rational decision-making and do not account for the effect of ecosystem services and conservation preferences on land management choices. IMPRESSIONS has used human behavioural models to study scenarios of individual and collective (political) dedication to conservation alongside climatic, economic and other drivers of change. This demonstrated that support for nature conservation at local and national scales was an important factor in maintaining scale and connectivity of natural areas (Brown et al., 2016). However, achieving preferred levels of conservation depends fundamentally on food demand and the intensity of agricultural production, with intensive production allowing land-sparing for conservation in other areas, and extensive production limiting scope for conservation except through multifunctional land-uses. These relationships were found to hold across scenarios, suggesting that areas subject to the greatest climate-induced land-use change (primarily towards the northern or southern extremes of Europe) will pose the greatest challenges, as well as opportunities, for nature conservation, requiring targeted political intervention if natural systems are to be protected (Holman et al., 2017).

Synergies between adaptation and mitigation

Synergies can occur between various responses to climate change, including between adaptation actions in the same sector (e.g. urban trees can both reduce runoff and also urban heat island effects) or in a different sector. Synergies can also occur between adaptation and mitigation. Clearly, at the global scale, mitigation reduces the amount of adaptation that is required to reduce climate change impacts to a particular level. It also reduces the rate of warming and therefore facilitates natural adaptation by ecosystems and species which are more likely to disperse sufficiently rapidly to track their climate envelopes. A number of adaptation measures that also could provide mitigation benefits have been identified (see Berry et al., 2015). For example, expansion of forests can increase carbon storage, as can wetland/coastal habitat creation providing they are managed to avoid potential increases in greenhouse gas emissions.
Some adaptation measures modelled in RISES-AM do have synergies with mitigation, especially those related to the use of coastal wetlands to increase resilience to SLR and enhance carbon sequestration. The restoration of coastal wetlands is a NBS, often used in combination with grey infrastructure, to increase the buffering capacity of coastal, estuarine and deltaic systems against climate change. In addition, coastal wetlands can be managed to optimize the sediment accretion rate (both inorganic and organic components) and thus increase the rate of carbon sequestration. Increasing land elevation with sediment supply from the river is a way to adapt to relative SLR and at the same time increase carbon sequestration in rice paddy fields. The stabilization of coastal sedimentary deposits through (re)vegetation or other nature-based solution (NBS) will reduce erosion and flooding risks and thus the need for a more continuous and artificial maintenance. This conclusion is applicable not only for deltas and low lying coasts, but also for most of the coastal systems considered, as fewer resources and less energy will be required to maintain a given land-sea border and thus it will reduce the carbon footprint of coastal protection.

How can nature conservation policies and practices be adapted to better deal with HECC?

The potential impacts of climate change on biodiversity will need to be taken into account in any future conservation policy or Biodiversity Strategy. However, as the integrated modelling has shown, there is a need also to take into consideration how climate change responses and policies in other sectors affect biodiversity, and how biodiversity policies (such as through restoration) impact climate mitigation and adaptation. Opportunities exist to reduce the pressures on biodiversity and to enhance nature conservation. Some of these might involve trade-offs, but others could provide synergies. For example, in the Water Framework Directive, waters in good ecological status are likely also to deliver water of a higher quality for domestic supply, while the appropriate application of green infrastructure and nature-based solutions have the potential to contribute to conservation, while also contributing to human well-being and other societal challenges, including climate mitigation and adaptation.

Nature-based solutions

Nature-based solutions (NBS) include climate change adaptation and mitigation measures, but they can also address other issues, such as sustainable urbanisation, restoring degraded ecosystems and enhancing risk management and resilience. In IMPRESSIONS, the main modelled NBS is the retreat of flood defences, through managed re-alignment. Retreat did not, however, cause a reduction in the number of people flooded or the damages arising at the European scale because the areas of habitat increase were relatively small and the habitats often not located in appropriate places. Nevertheless, managed retreat has been shown in other studies to be an effective NBS.

In RISES-AM, NBS were analysed in the Rhine and Ebro deltas. The restoration of coastal wetlands, often in combination with grey infrastructure, increases the buffer capacity of coastal, estuarine and deltaic systems against climate change. This is the case for the room-for-the-river type of solution that is being implemented in the Rhine Delta, an adaptation measure that provides buffer capacity against both marine and fluvial flooding risks associated with extreme events. Increasing land elevation or “rising grounds” as it has been named is a promising NBS that can be potentially applied to many low-lying areas to adapt to climate change. For instance, sediment supply from the river was a way to adapt to relative sea-level rise that was applied in the past in the Ebro Delta to create rice fields in salt-marsh areas. The enhanced capture of sediments was also how many polders were developed in the Rhine Delta. The supply of fresh water and sediment to swamps and marshes is also being applied in the Mississippi Delta. These types of NBS can also be applied to other delta systems worldwide, such as the Asian mega-deltas.

Human health

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Contributing Author: Simon Lloyd

Key messages

- Higher temperatures could have significant impacts for health and wellbeing including human comfort, particularly in southern Europe.
- Under high-end scenarios, high temperatures after mid-century would be expected to alter patterns of daily living and working.
- Autonomous adaptation could offset significant impacts but there will be limits to adaptation to higher temperatures.
- Adaptation strategies relating to new build and retrofitting of dwellings has implications for mitigation policy unless energy-intensive space-cooling is avoided.
- Climate change is projected to increase child undernutrition in sub-Saharan Africa and South Asia, but research is needed to understand the full implications of the high-end scenarios.

Policy context

Extreme weather has significant impacts on economic sectors, as well as adverse social and health impacts on European populations, and impacts on populations outside the EU28 will also have implications for EU policy.

Climate change will increase the frequency and the intensity of hot weather - which is associated with significant acute impacts on mortality and morbidity. All populations are affected by high temperatures, but it is not known how quickly populations can adapt or the limits to this adaptation. High temperatures are likely to have future effects on the capacity to undertake activities outdoors - whether for leisure or employment. One direct effect of a higher number of very hot days is likely to be the "slowing down" of work and other daily activities. Whether it occurs through "self-pacing" (which reduces output) or occupational interventions (which increases costs), the end result is lower labour productivity and possibly an increase in occupational heat injury and death. There will also be health benefits from milder winters in terms of the reduction of cold-related mortality or morbidity.

Adaptation measures to reduce heat health effects include heat-wave plans, improvements in urban planning and housing design (including retrofitting) and social protection measures for older and vulnerable citizens. Future changes in housing and infrastructure have the potential to reduce the regional or local burden of heat-related mortality.

There will be important differences in impacts within Europe: populations in southern Europe appear to be most sensitive to hot weather, and also will experience the highest heat exposures in the future in absolute terms. Populations in central and northern Europe are also vulnerable to heat-wave events. The adaptive capacity of populations is likely to vary significantly within Europe.

Policy insights

What is the impact on acute mortality from high summer temperatures under high-end scenarios and a changing urban environment?

Climate change is projected to increase heat-related mortality in all populations but impacts are greatest under high rates of warming (indicated by RCP8.5 emissions scenario). Results are presented as absolute annual numbers and not rates meaning population size needs to be taken into account. Figure 26 illustrates that future burdens without adaptation are very different across Europe, with southern and central Europe showing particularly large increases in heat-related mortality. Currently, high temperatures have the greatest effect on acute mortality in southern Europe, shown in several epidemiological studies. As would be expected, the impacts are greatest under the highest warming (RCP8.5) and towards the end of the century. The impact of climate variability is also apparent. This model projects higher estimates of mortality effects than a previous model that used a linear association to model the association between temperature and mortality.

Urban heat islands (UHI) are a factor in many urban settlements and refer to the difference in temperatures measured inside and outside the urbanised area. High ambient temperatures have impacts on thermal comfort, productivity, energy use, and human health. Several studies have quantified the role of the built environment in increasing outdoor temperatures. The UHI intensity is typically higher at night than during the day and shows seasonal variation, typically greater in winter than in summer. Results from RUGv4.0 show that urbanisation trends in Europe are fairly modest under the range of SSP scenarios. Thus, changes in outdoor temperature due to increases in high density urban areas are not likely to be a key factor for future heat-related mortality.

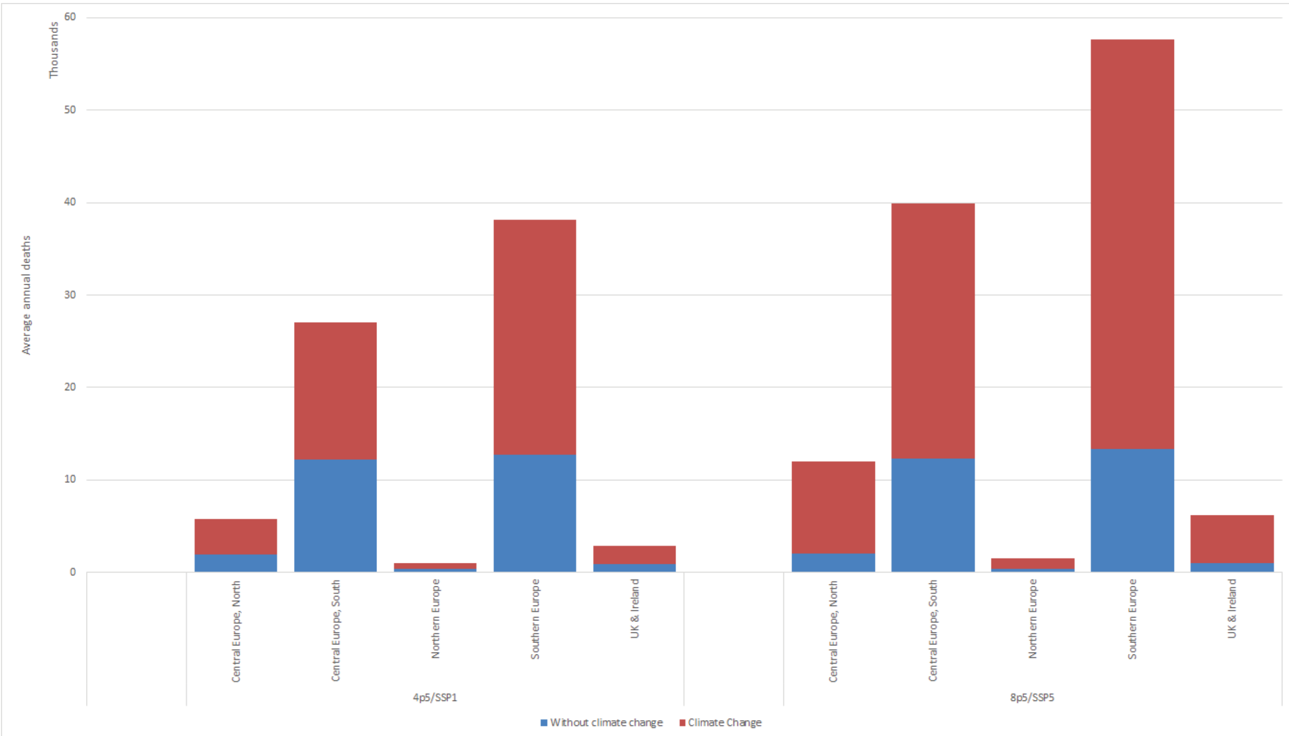

Figure 26. Future annual heat-related mortality in Europe, with and without climate change in 2050s. {no adaptation or acclimatization) [Preliminary results, from IMPRESSIONS].

How does population growth and aging, and population movement interact to affect health risks under high-end scenarios?

The impact of climate change on heat-related mortality is very dependent on future rates of population aging. Population growth is only a determinant to the extent that the number of older persons is increased. Populations in Europe are aging, and projections show that the number of elderly and very elderly is likely to increase dramatically after mid-century[1]. Studies of healthy aging also indicate that there is considerable uncertainty about the vulnerability of Europe's older citizens to weather extremes.

Where and when will temperature exceed citizen's comfort?

Much is known about human responses to local variations to temperature and humidity, and the weather conditions that are reported as pleasant or tolerable. However, there is only limited value in mapping these indices at large scale now and in the future as individual responses will be determined by local bioclimatic conditions, particularly if the person is indoors. Limited evidence regarding current behaviour indicates that people have a relatively high tolerance for high temperatures for leisure activities and more research is needed to determine the thresholds which are likely to trigger significant changes in human behaviour.

However, significant changes in temperature are projected. For example, Figure 27 illustrates the increased frequency of heat alerts and heat alarms in two populations in Hungary, based on thresholds determined by the local public health agency.

During the summer, increases in indoor overheating are likely to increase discomfort and, potentially, a rise in cooling demand following an increased uptake of active cooling systems. Modelling studies suggest that as the climate becomes warmer, it will be increasingly challenging for naturally ventilated buildings to maintain comfortable indoor thermal conditions using passive ventilation-based measures alone (Zero Carbon Hub, 2015a, b, c).

1 http://ec.europa.eu/eurostat/web/population-demography-migration-projections/population-projections-data

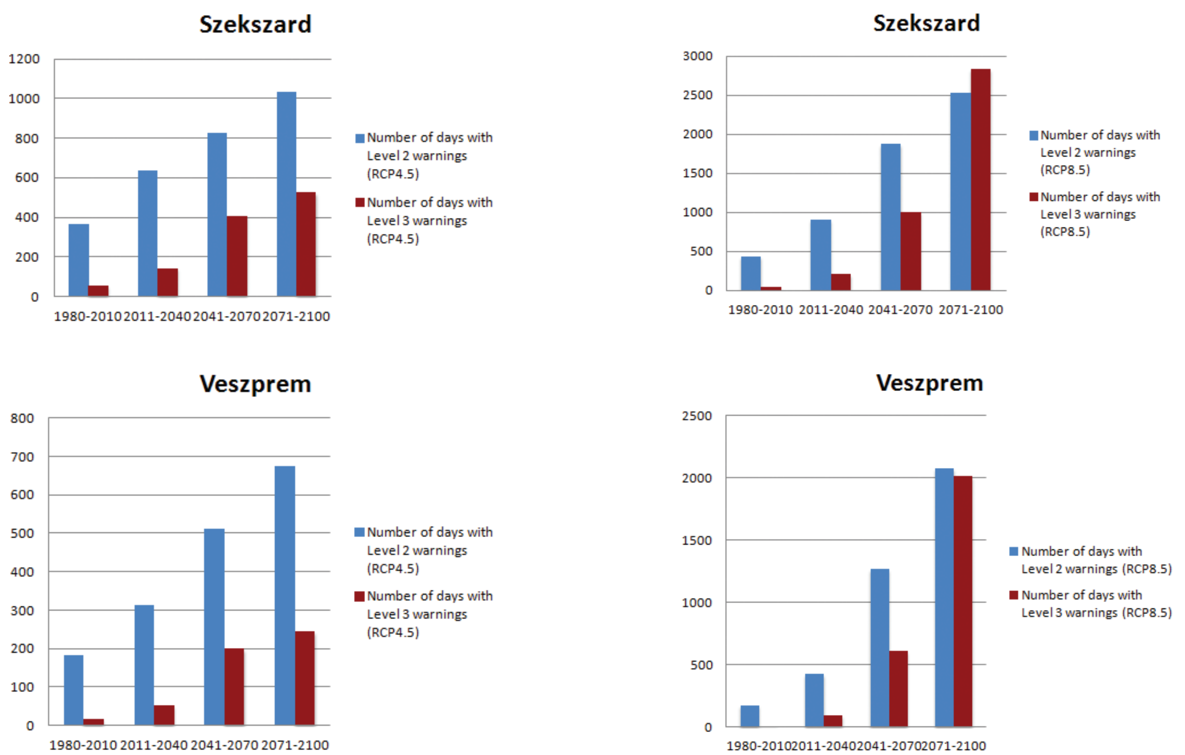

Figure 27. Increased frequency of heat alerts and heat alarms in Szekszard and Veszprem, Hungary, based on RCP4.5 (left) and RCP 8.5 (right) from IMPRESSIONS. Note the y axes scales are not the same.

How will climate change affect malnutrition under high-end scenarios?

Malnutrition is a significant health problem in low- and middle-income countries, and is a priority within EU policy on international development. Child undernutrition is associated with mortality, morbidity, and lifelong consequences such as reduced learning and earning capacity. In 2011, 165 million children were stunted, contributing to around 45% of all child deaths (Black et al., 2013).

Impact estimates vary by scenario and model, but results so far suggests that moderate to high climate change may increase stunting by 23% in parts of Africa and 62% in South Asia by 2050 compared to a world without climate change. The implications of 'high-end' scenario (assessed via RCP8.5) indicate even higher effects on stunting, particularly in South Asia. The model assumed that the relationships between the observed variables and the dimensions of food security are constant over space and time.

The causation of stunting is complex, as social and economic factors that determine access to food are as important as food production or food availability. To date, global food security assessments have focussed on the pathway from climate change to reduced crop productivity to child undernutrition, with the key input variable "post-trade national-level per capita calorie availability". Many other key factors that will shape future nutrition are not directly considered within integrated assessment models. Research for IMPRESSIONS takes a 'food security' perspective and explicitly represents dimensions for 'availability' (i.e. how much food available?), 'accessibility' (i.e. can people access the available food), and 'utilisation' (i.e. are people able benefit from the food they have access to; for example, repeated episodes of diarrhoeal disease may prevent this). This provides a more detailed analysis of the factors contributing to future patterns of undernutrition under different climatefutures.

Urban

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Key messages

- Artificial surface extent could vary from about 4% of the European land area today, to approximately 4% to 9% of that area by 2100, depending on the socio-economic scenario.

- Population change is a key driver of future artificial surface expansion. However, changes to the demographic profile of this population, their residential preferences and planning legislation have the potential to restrict or magnify patterns of growth. A declining population does not imply a static artificial surface extent in the presence of changing residential preferences.

- The contrasting residential profiles of each socio-economic scenario influence the extent and location of artificial surface. The dense urban networks of Belgium, the Netherlands, western Germany and southern United Kingdom promote concentrations of future suburban development. This is in contrast to the 'hotspots' of development that are more sparsely distributed across, for example, Spain, Portugal and the Nordic countries.

- Sprawling urban development could place greater pressure on sensitive ecosystems as the population in close proximity to protected areas, water bodies and coastal regions increases.

Introduction

The artificial surfaces associated with urban areas cover approximately 4% of land surfaces within Europe. Despite this, cities, towns and suburban areas are home to over two-thirds (72.4%) of the European (EU-28) population (Eurostat, 2015). Furthermore, urban areas account for ~80% of energy use (EC, 2016a), contribute ~69% of European CO_2 emissions (EEA, 2015) and generate up to 85% of Europe's GDP (EC, 2016a). It is in this context that urban areas are key in confronting a number of global challenges.

Urban areas are embedded across European policy; it is estimated that two thirds of all European sectoral policies have an impact on urban areas (Van Lierop, 2015). Approximately 50% (~80-90 billion Euros) of the current European Regional Development Fund (ERDF) will be invested in urban areas (EC, 2014) with sustainable urban development prioritised in Articles 7 to 9 (EU, 2013). Objective eight of the 7th Environmental Action Programme, Europe's environmental policy focus until 2020, specifically targets sustainable urban cities (EU, 2011a). Urban areas have a key role in the implementation of the Europe 2020 priorities of smart, sustainable and inclusive growth (European Commission, 2010). Urban areas form the basis of European initiatives, such as ESPON, URBACT, EUKN, RFSC and JPI Urban Europe. In the context of climate change, urban carbon emission reduction initiatives include the "Covenant of Mayors"; a commitment by local authorities to exceed the European CO_2 reduction target of 40% by 2030 (CMCE, 2015). The importance of urban areas within Europe and the diversity of policy challenges confronting them is leading to increasing intergovernmental cooperation in the establishment of a European Urban Agenda (European Commission, 2016b).

Urban areas are dynamic with interacting factors, such as, (i) a changing population and demographic structure, (ii) changing cultural/societal values, living standards and lifestyles, and (iii) policy driving their future form and function. Future urban areas are not without their own challenges, for example, they must: (i) adapt to demographic change as a consequence of an aging European population and migration, and (ii) deal with the social and environmental implications of climate change. Indirectly, urban areas have an important influence on biodiversity loss, society's capacity for food generation and long-term resilience of ecosystem services. Such challenges highlight the need for projecting future urban expansion and reflecting on the implications for policy development.

This chapter considers the structure and extent of future urbanisation under a set of alternative socio-economic scenarios. Modelling outcomes are primarily presented at a pan-European scale via the RUG (v4) model. However, regional scale variability is also discussed with focal studies based on a detailed urban model developed specifically for Hungary.

The pan-European scale model (RUG), disaggregates artificial surfaces (associated with human settlements and manufacturing activities) into four distinct classes; (i) urban, heavily populated city centres, (ii) suburban regions, that is, less densely populated urban areas/conurbations, (iii) sparsely populated rural villages, hamlets and small towns, and (iv) non-residential, industrial and manufacturing areas.

Future socio-economic scenarios are based on the SSPs (shared socio-economic pathways) specifically developed for Europe (Kok and Pedde, 2016). SSP storylines form the basis of RUG parameterisation. For example, changing planning legislation and societal preferences control the distribution of the population across each residential type and density at which they reside. Such parameters will mitigate/magnify urban expansion (Figure 28). The location of this expansion is controlled by societal preferences, within each SSP, which describe whether society seeks to reside in close proximity to (i) green open spaces or urban areas, and (ii) landscape features such as the coast, waterbodies and protected areas (Figure 28).

How might artificial surface expansion vary across Europe?

The extent and spatial pattern of future artificial surface expansion is highly dependent upon the socio-economic scenario considered (Figure 29); artificial surface extent varies from 4% (SSP1, SSP4) to 9% (SSP5) of the European land area by 2100. At a European scale, SSP5 is characterised by urban sprawl; artificial areas expand to an area over twice that of SSP1/SSP4 by 2100. This sprawl parallels the scenario storyline in which a growing, individualistic and wealthy society seeks larger properties in suburban and rural areas. Urban sprawl of this magnitude will (i) increase the competition for land (for example, with food production or nature protection), and (ii) detrimentally impact ecosystem services and biodiversity. The Cities of Tomorrow report states that "urban sprawl and the spread of low-density settlements is one of the main threats to sustainable territorial development" (EU, 2011b).

Although driven by different mechanisms, limited artificial surface increases are predicted in SSP1 and SSP4; a reflection of the scenario storylines. Within SSP1 an increasingly environmentally aware society shifts towards more sustainable, higher density living; a shift that mitigates substantive artificial surface expansion. The vibrant and attractive urban areas of SSP1 are, however, in stark contrast to the urban ghettos of SSP4. In this scenario, urban living is a consequence of a poorer society migrating to urban centres in search of jobs and social services.

At a sub-European scale, a clear distinction exists in the modelling outcomes of selected eastern countries (BG, HR, LT, LV and RO) and the rest of Europe; a distinction driven by demographics. These eastern countries are, within SSP5, characterised by an aging, but overall decreasing population (IIASA, 2015); a distinct contrast to the population increases associated with SSP5 in the remainder of Europe. Consequently, minimal artificial surface expansion is projected in the specified eastern countries under SSP5. In this region, the artificial surfaces increase is most substantial in SSP3. While this scenario is also

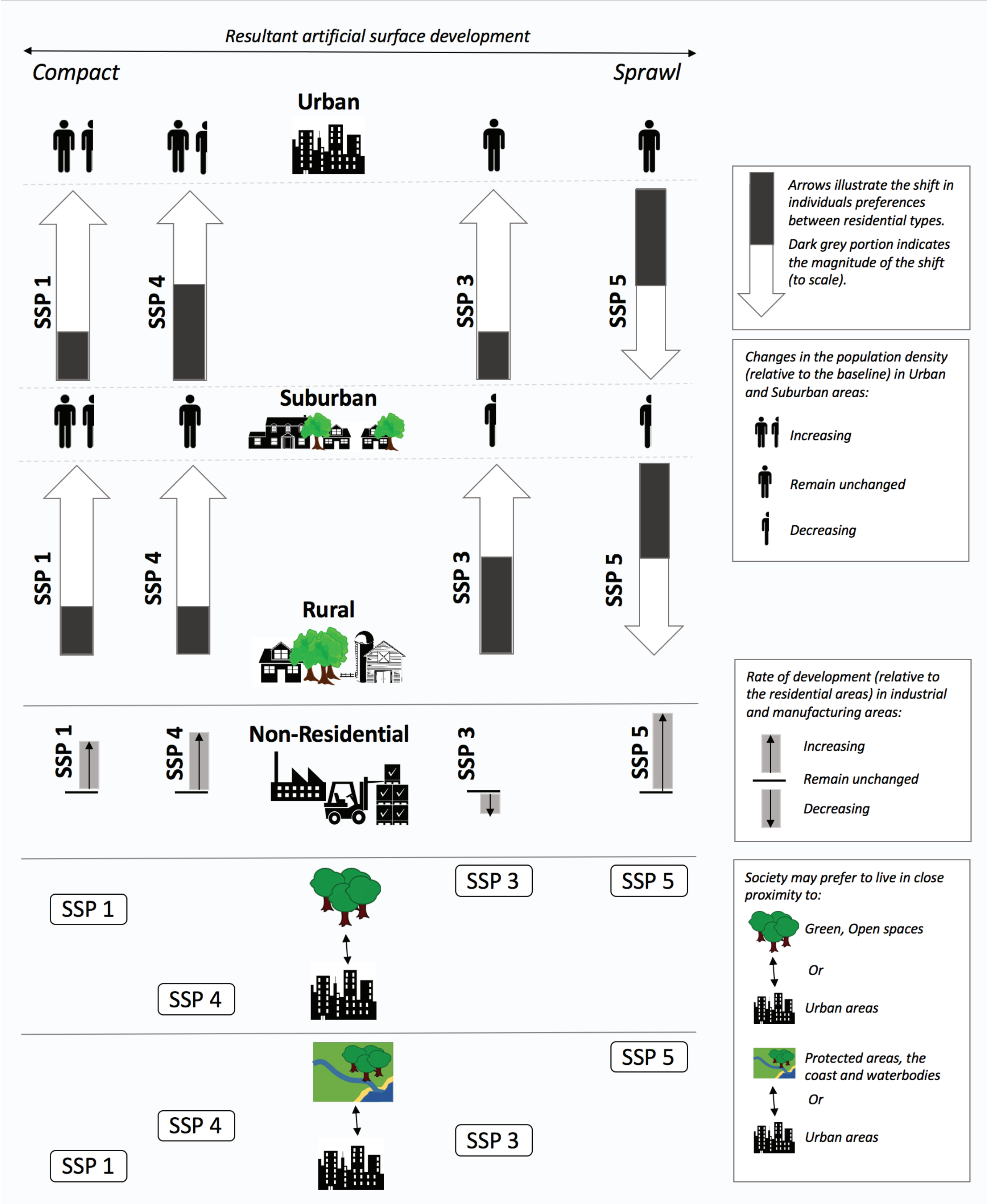

Figure 28. Parameterisation of the pan-European RUG model within the context of the European SSPs, from IMPRESSIONS.

characterised by an aging and declining population, a slow rate of change combined with a shift towards suburban development (associated with urban in-migration and weak planning laws) results in artificial surface expansion.

The SSPs highlight the potential extent of future artificial surface change under very different socio-economic circumstances. Important distinctions between the scenarios include (i) the potential to mitigate artificial surface expansion

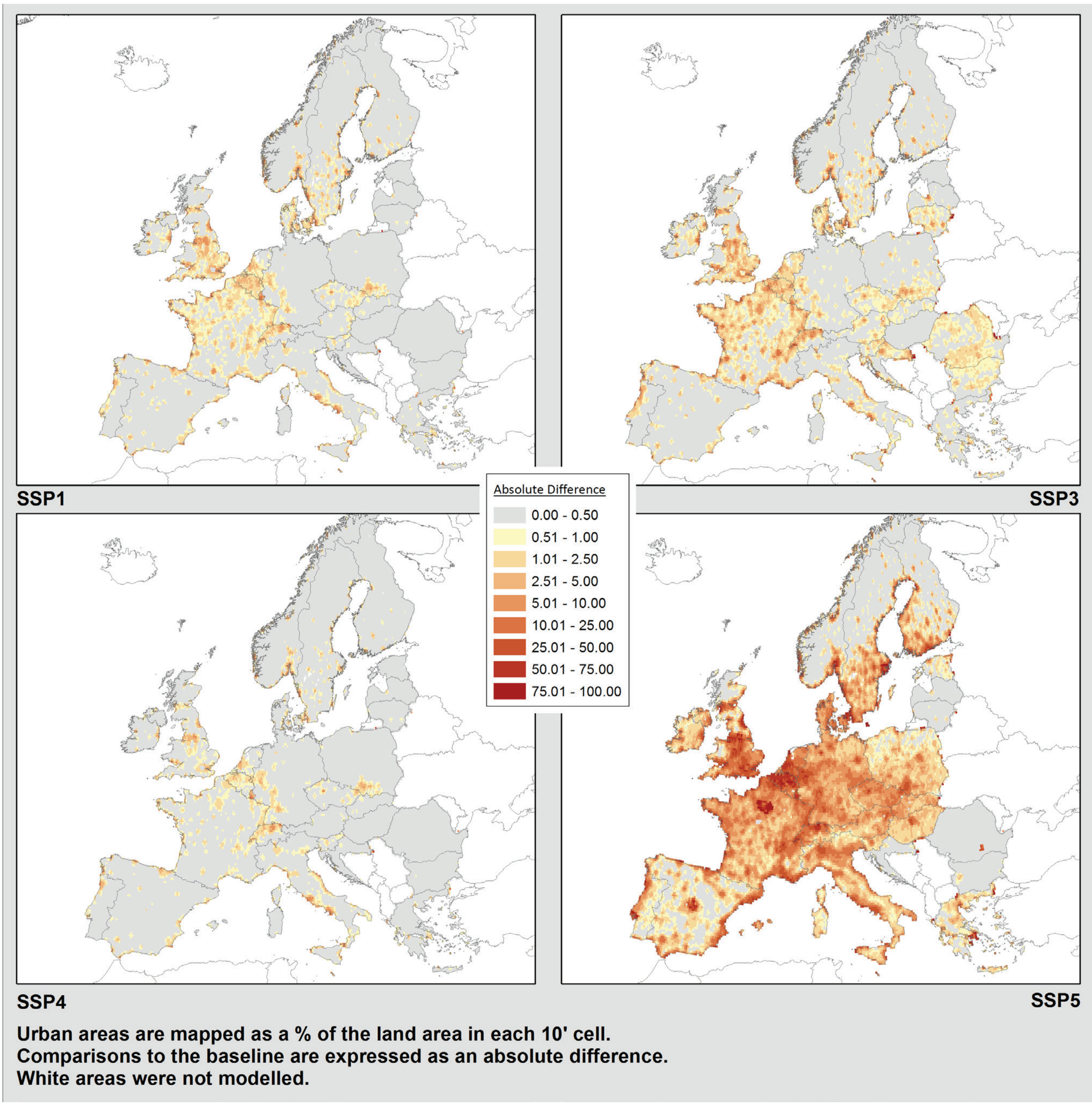

Figure 29. The projected change, from baseline, in artificial surface extent by 2100 under four different socio-economic scenarios. Darker colours are associated with greater artificial surface expansion, from IMPRESSIONS.

via increasing population densities (as evident in SSP1), (ii) the potential of artificial surfaces to 'sprawl' in the presence of increasing populations, and/or changing residential preferences (SSP5), (iii) the influence of changing residential habits which do not guarantee a static artificial surface footprint when populations decline (selection of countries in SSP3), and (iv) regional variability in artificial surface expansion.

Sustainable urban development is characterised by compact urban forms which promote, (i) reduced car reliance and travel times improving energy efficiencies and promoting public transport, (ii) improved social service provision, (iii) higher population densities and an associated reduction in the heating/energy costs, and (iv) circular economies typically associated with increased resource efficiencies. Such characteristics are most paralleled by the outcomes of SSP1, which promotes a shift towards higher density urban centres.

Box 1. An example of local scale modelling for Hungary

Modelled urbanisation change, within Hungary, is based on a region specific model of urban development and associated socio-economic scenarios. These scenarios while based on the European SSPs have been specifically co-developed for the region with local stakeholders.

Within Hungary, artificial areas (of all types) are projected to increase from 5.4% of the Hungarian land area in 2010 to between 6.2 and 8.4% in 2100. Increasing artificial areas are observed in all scenarios. The only exception to this trend is SSP3 in which no urban expansion occurs between 2070 and 2100 (a specification of the scenario storyline). Following the patterns observed in Europe, SSP5 is projected to lead to the greatest urban development; artificial surfaces increase (sprawl) by 48.3%. As the population of Hungary increases in SSP5, the population density (inhabitants per km^2 residential area) of all urban areas is projected to increase. It is not until 2070 and beyond that, due to the sprawling development, as assumed under SSP5, that population densities start to decline within the major urban areas, that is, capital and the regional centres.

A characteristic of all the socio-economic scenarios in Hungary is a major "population flow" and peri-urbanisation of Budapest. Populations are projected to move from both (i) the city-centre to suburban (fringe) areas of the capital, and (ii) from Pest county to the capital. These projections suggest that future local urban policies should take into consideration the potential underutilisation of urban infrastructure within the capital (to minimise sprawl) and the additional pressures of ensuring social service provision in suburban (fringe) areas. Following the patterns observed in Europe, SSP1 is most paralleled with sustainable urban development as it (a) promotes compact development, and (b) ensures that, in spite of a declining national population, population densities are maintained (or only slightly decrease) in the capital and regional centres.

What is the effect of land-use planning and residential preferences on future urban development across Europe?

Life-cycle stage has been identified as a predominant factor in defining the residential location of an individual/household (Fontaine and Rounsevell, 2009; Fontaine et al., 2014). The inclusion of residential preferences, the link between population demographics and 'preferred'[1] residential type, enables the RUG model to explore the construct of future urban areas.

Sprawling urbanisation within SSP5 (Question 1) was attributed to an increased population and shift in preference towards more expansive residential types. This shift is clearly evident in the (i) projected artificial surface profile of the SSP5 scenario which is primarily constructed of suburban/town (36%) and rural (38%) areas by 2100, and (ii) rate of change projected for each artificial surface type; suburban/town and rural areas triple or double, respectively, in their extent in comparison to relatively static urban centres.

European scale statistics mask underlying variability, as exemplified for the suburban residential type (Figure 30), driven by (i) regionally variable demographics and/or residential preferences, and (ii) a strong correlation between new developments and the existing artificial surface network. Cities, and their associated suburbs, within Belgium, the Netherlands, western Germany and southern United Kingdom, are characterised by their close proximity. Future suburban developments are typically focused in these densely populated regions; highlighted by the concentrated artificial surface change (darker colours) of Figure 30. By contrast, Den-

1 Changes to societies' residential 'preferences', as defined in RUG, can represent a choice driven by an attraction/like or a forced shift required to satisfy a need (for jobs, access to social services etc.).

mark, Sweden, Finland, France and the interior of Spain and Portugal are characterised by more sparsely distributed cities. Suburban expansion (Figure 30) tends therefore to be associated with 'hotspots' of change around existing cities. These regional differences highlight contrasting sustainable development challenges. Planning in the compact cities of the Netherlands and Germany is focused on achieving sustainable urban densification while accommodating green space so as to be prepared for climate change challenges, such as flooding and heat stress. For cities in France and Sweden the challenge is how to balance future suburban expansion while protecting green space at the suburban-urban interface.

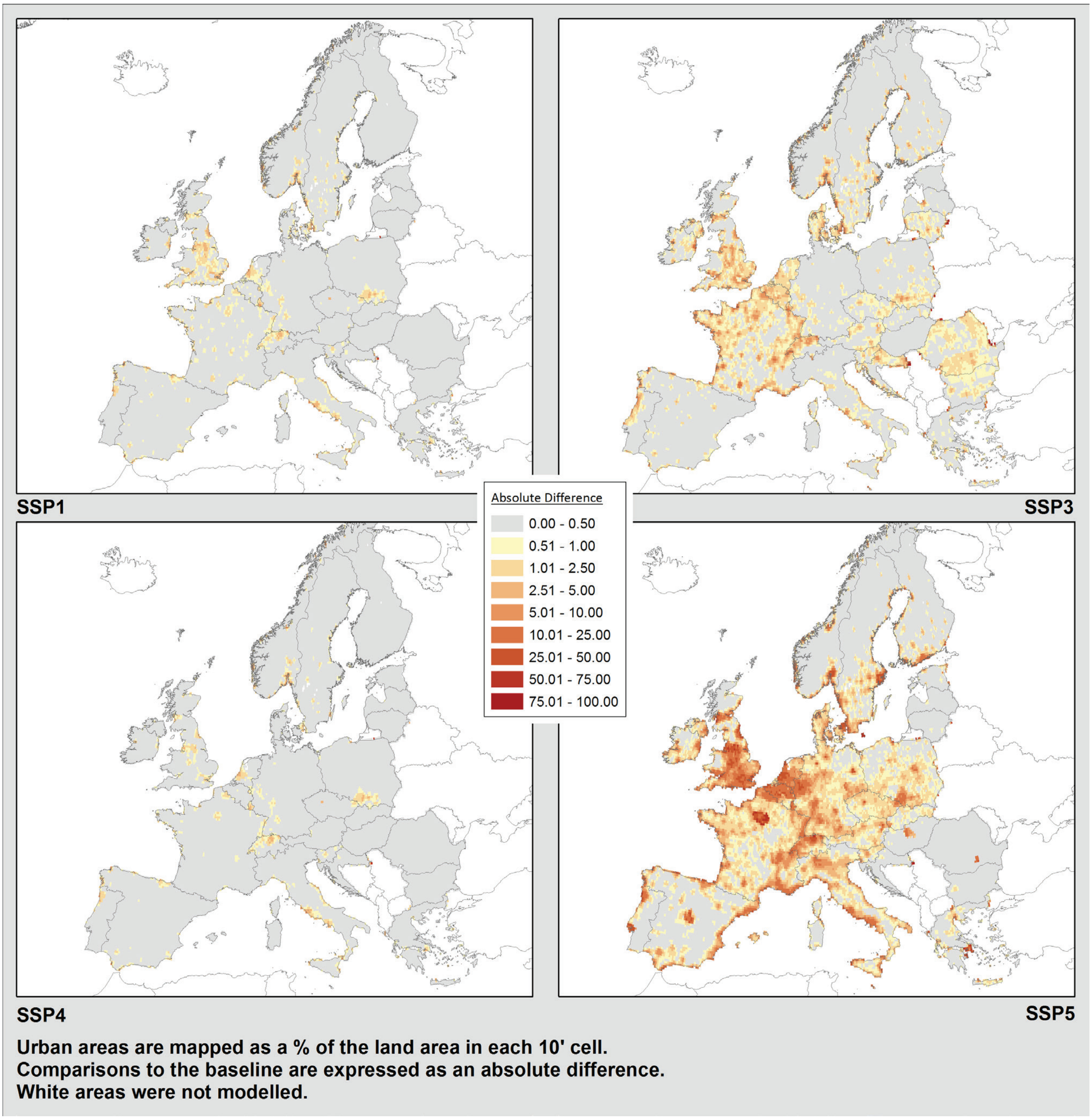

Figure 30. The projected change, from baseline, in suburban areas by 2100 under four different socio-economic scenarios, from IMPRESSIONS. Darker colours are associated with greater artificial surface expansion.

How might urban, suburban and rural populations change under future socio-economic scenarios?

Population projections project, at a European scale, an overall increase in population in the SSP1 and SSP5 socio-economic scenarios. Conversely, SSP3 and SSP4 are characterised by declining (and aging) populations (IIASA, 2015). Modelling the SSP storylines for this overall demographic change, and link between life-cycle stage and residential preferences, allows RUG to explore the residential circumstances of this future population (Figure 31).

At the European scale, the increasing population projected in SSP1 predominantly resides in cities, which account for a higher proportion of the total population (44%) when compared to the baseline (36%), (Figure 31b). An increasingly city dwelling population is evident in SSP4 where cities become the predominant residential type, housing 53% of the population (Figure 31b). The largest change in the residential structure of the population, at a European scale, is observed in the urban sprawl of SSP5; a substantial decrease in the proportion of the population resident in cities (declining to 18%) and increasingly suburban (36%) /rural (46%) population (Figure 31b).

The RUG model assumes that existing artificial surfaces are maintained. Further, populations are assumed to reside in their preferred residential type; they are not forced to populate the existing artificial surface footprint. Consequently, it is viable for population densities, within existing urban areas, to decrease, replicating processes of artificial surface abandonment. This is reflected in the declining city-based population of SSP5. This could lead to urban decline via the abandonment of buildings and associated social issues (crime, poor quality housing) or the development of increased urban green space and/or 'gentrification' of city areas. In a contrasting process, the declining population of rural areas, particularly within SSP3 (which falls to 15%; Figure 31), are indicative of rural abandonment. This abandonment is likely to be associated with increased social problems within rural areas (due to the closure of services) and may impact the availability of labour in the agricultural sector. Historically, rural – urban migrants have encountered increased social problems (unemployment and/or low paid work, lack of adequate housing) within their new urban environments.

Residential types are a key indicator of access to social infrastructure such as education, health-care, and broadband. A shift towards the higher density urban areas in SSP1, and to some extent SSP3 and SSP4, is advantageous in terms of ensuring service provision and transport efficiencies. Currently, approximately 68%

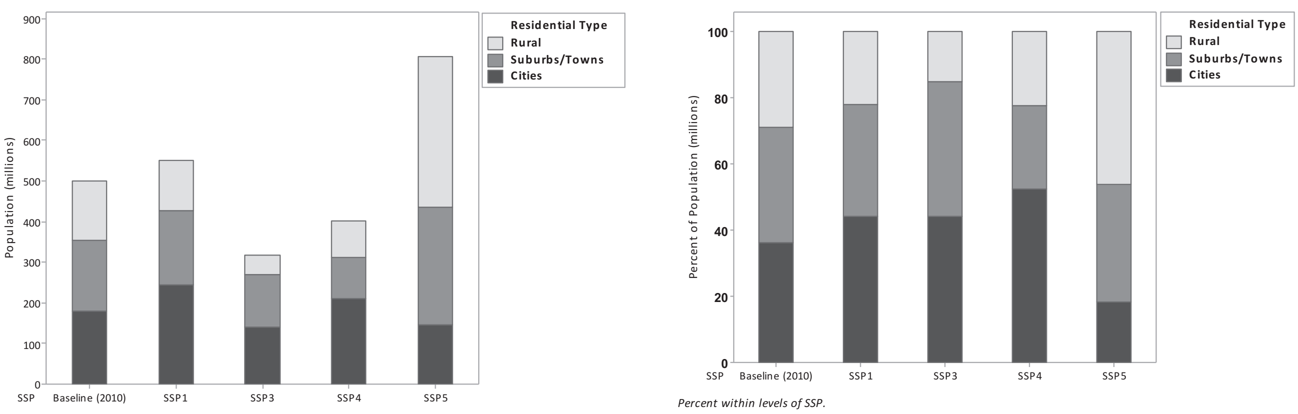

Figure 31. European scale population as a function of residential type at 2100 under four socio-economic scenarios; (a) Population count (Millions), and (b) proportional representation, from IMPRESSIONS.

of Europe's population have 'ease of access'[2] to a city, this proportion increases substantially to ~80% to 85% in SSP1, SSP3, and SSP4. However, these advantages are unlikely to be realised in the socio-economic circumstances of SSP3 and SSP4. The dense cities and urban ghettos of SSP4 highlight regions where social issues are typically prevalent (unemployment, poverty, segregation, exclusion, crime etc.) and urban regeneration policies should be targeted. The urban sprawl of SSP5 does not promote efficiencies in the provision of public services; a shift to suburban/rural based populations is indicative of distributed service provision. This poses key environmental challenges in regard to, for example, achieving emission reduction targets given the foreseen use of cars rather than low-carbon public transport.

Currently, up to one third of Europe's city populations are exposed to air pollution levels in excess of air quality standards (EEA, 2015), while half are exposed to excessive traffic noise (EEA, 2015). The SSP3 and SSP4 storylines describe poor urban planning, urban ghettos and low levels of environmental/social awareness; conditions likely to magnify current city-based pollution issues and social challenges such as cohesion and segregation. In these scenarios not only are planning and governance structures weak but, the capacity of society to reflect on the long-term consequences of its choices are lacking; circumstances which, when combined, are likely to exacerbate current socio–ecological problems. The cities described in SSP1 are environmentally friendly and designed to promote human well-being. However, to achieve this societal goal in dense urban areas, green spaces, building and infrastructure design must be properly planned and managed to mitigate the known negative human health effects.

How might the vulnerability of an urban society vary under future socio-economic scenarios?

Socio-economic scenarios which are based on sustainable urban development, such as SSP1, have been demonstrated to promote slower rates of artificial surface development and more compact urban forms. Such development promotes, inter alia (i) efficiencies in transport, social service provision and resource use, (ii) minimal land competition, and (iii) improved air, noise, water and environmental quality. Sustainable development scenarios are strongly dependent upon an increasing (and substantial) shift in societal preferences to high-density, environmentally friendly city living. Social change, strong planning and/or regulation are required to achieve the targeted residential densities of city areas while ensuring green spaces, building and infrastructure design are correctly planned and managed to mitigate the known human health effects and social problems common in densely populated urban areas.

Contrasting SSP1 to SSP3 and SSP4, it is evident that an increasingly urbanised population can arise independently of sustainability concerns. These alternate scenarios lead to urban ghettos (SSP4) and urban sprawl commensurate with countryside abandonment (SSP3). The urban densification associated with SSP4 does minimise artificial surface change and associated land competition issues. However, the resultant urban ghettos are likely to be characterised by high levels of social problems and poor environmental quality. The urban sprawl in SSP3, while significantly less than in SSP5, is poorly planned and therefore likely to impair ecosystem service provision. As a consequence, both scenarios are likely to result in an increasingly urbanised society, which has a lower coping capacity and higher vulnerability to climate change.

Sprawling artificial surface expansion from ~3% to ~9% of the European land area, under SSP5, exacerbates competition with the agriculture and forestry sectors, leading to an increasingly urbanised population having to balance the ability to meet demand in terms of food and resource supply. Within this scenario, there is a projected greater than 60% increase in the number of people with 'ease of access'[2] to existing protected areas. Such access to green space is known to be beneficial from a human well-being perspective. However, such large increases in the population adjacent to natu-

2 Defined as the proportion of the population residing in or within the same 10' cell as a city area.

ral areas is likely to put increasing pressure on fragile ecosystems, the services they provide and the biodiversity they support. Similar increases are observed in the population in close proximity to a waterbody (59% increase) and the coast (83% increase) having significant implications in terms of the vulnerability of population to flooding, the extent of remedial engineering required to mitigate this and the potential impacts on these ecosystems and the services they provide. The patterns of artificial surface development observed in this scenario have been identified as a serious threat to Europe's sustainable urban agenda (EU, 2011b).

Climate impacts in an increasingly globalized world

Lead Authors: Henrik Carlsen and Nakia Pearson

Key messages

- Transnational climate change impacts could have substantial effects on Europe. High-end scenarios could imply increased systemic effects of climate change, including cross-sectoral and transnational climate impacts. However, research on the physical as well as governance aspects of transnational climate impacts is still in its infancy.

- Transnational climate impacts still play a minor role in the EU, as well as in Members States' adaptation policies. The potential international dimension of climate impacts may provide incentives for more collaboration between EU Member States, as well as between the EU and other parts of the world.

Policy context

The international dimension of climate change has mostly been framed around efforts to mitigate emissions of greenhouse gases, while adaptation planning has often taken a predominantly territorial approach by only assessing impacts of climate change emerging within each country's borders. However, in an increasingly globalized world, no country is fully insulated from the impacts of climate change outside its borders. Hitherto this aspect of climate change has only played a minor role in EU policies.

The following table briefly describes key EU policies of relevance for addressing climate change beyond Europe's borders. While the selection is not exhaustive, it includes the most relevant policy areas. One exception is the EU Adaptation Strategy which is briefly discussed in the final section.

EU Policy Competence of Relevance for Transnational Climate Impacts

Policy Competence	Summary
Climate Action for Developing Countries	EU is largest contributor (80%) of climate science to developing countries, with a spending focus on mitigation. EU has pledged to the UN Green Climate Fund to finance developing countries' transition to low-emission and climate-resilient development pathways.
Humanitarian Aid In the Framework of Climate Disasters	EU planners have begun to assess climate factors as part of conflict management scenario building and to tighten coordination with the EU Civil Protection Mechanism in facilitating EU emergency responses. The Disaster Preparedness ECHO programme (DIPECHO) aims to increase resilience and preparedness of at-risk communities, and to reduce their vulnerability by training, establishing or improving local early warning systems and contingency planning.
Trade	A lack of precise language in both the Transatlantic Trade and Investment Partnership (TTIP) and Comprehensive Economic and Trade Agreement,(CETA) deal that would otherwise compel investors to take environmental and other social protections more seriously into account, thereby ensuring better coherency between trade and environmental values in EU Trade Policy.
Climate Action for Europe's Neighbours	EU Neighbourhood Policy (ENP) supports climate change mitigation and adaptation in the EU's closest eastern (Clima East) and southern (Clima South) neighbours. Financial and technological assistance is employed towards strengthening the capacity to reduce greenhouse gas emissions, preparation for climate change impacts, climate resilience and economic development and employment. The programme lacks development strategies within mobility partnerships (MPs) that focus on climate adaptation and resilience strategies.

Policy Competence	Summary
Climate Security	Military missions, as part of EU's Common Security and Defense Policy (CSDP), mainly focus on disaster response and maintaining stability, rather than disaster preparedness. Investments are occurring in the Global Monitoring for Environment and Security system with satellites and other capabilities to collect data. Early warning enhancement specifically linked to climate change are not clear or easy to operationalise (Youngs, 2014).
Migration	EU external migration policy in the Global Approach to Migration and Mobility (GAMM) officially recognises climate-induced migration, but "the voluntary and selective nature of its implementation" significantly erodes its ability to promote climate adaptation within mobility dialogues (Blocher, 2016). Within Europe, few countries' legislation explicitly protects environmentally displaced people (Kräler et al., 2011). The EU Lisbon treaty does not address disasters in non-member states, neither does it treat instances of the cross-border movement of EU citizens within Europe in the context of disasters (Kälin and Schrepfer, 2012).

Transnational climate impacts

In order to understand these transnational climate impacts (TCI) IMPRESSIONS has developed a conceptual framework (Benzie et al., 2016) including four risk pathways:

- The biophysical pathway encompasses transboundary ecosystems, such as river basins, oceans and the atmosphere;
- The finance pathway represents capital flows and climate impacts on assets held overseas;
- The people pathway involves the movement of people between countries, e.g. tourism and migration;
- The trade pathway transmits climate risks across international supply chains.

Transnational climate impacts are transmitted across borders along these four risk pathways, affecting one country – and requiring adaptation there – as a result of climate change or climate-induced extreme events in another country.

Figure 32 provides a preliminary assessment of Europe's exposure to transnational climate impacts compared to climate risks that emerge within each European country's borders. The map is constructed by identifying and quantifying individual indicators along the four risk pathways, e.g. migration from climate vulnerable countries in the people pathway and cereal import dependency in the trade pathway, as well as an indicator assessing a country's embeddness in the global context.

It is evident that while Europe ranks low on the (global) index assessing climate risks emerging from within each country's border, the picture with regards to transnational climate risks

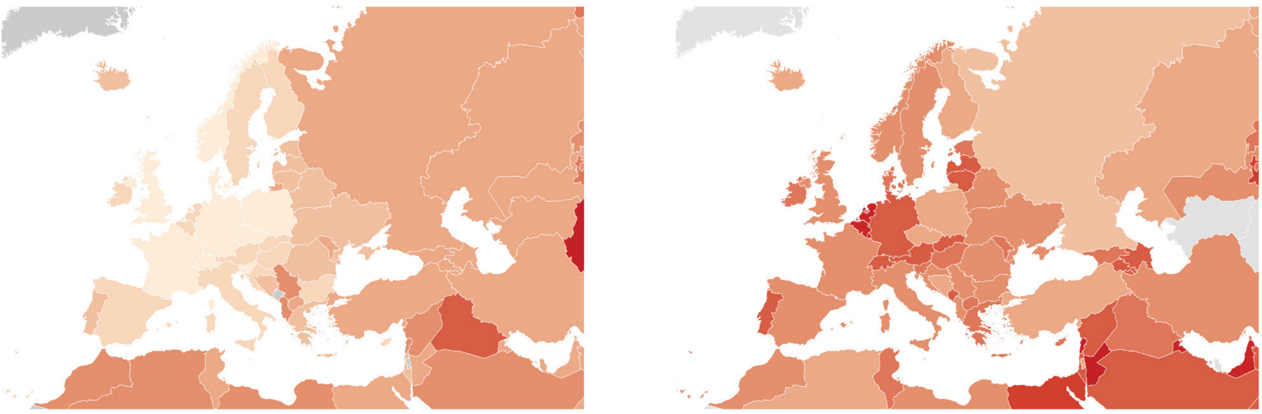

Figure 32. Comparing climate risks for European countries using two different indices: ND-GAIN and the TCI index , from IMPRESSIONS. The left map shows climate risks emerging from within a country's borders while the right figure shows exposure to transnational climate risks.

is much more mixed. One example of a country scoring low on both indices is Poland. Several European countries score high on transnational climate risks, but for different reasons. Portugal's high score is mainly due to high reliance on transboundary water (biophysical pathway). Likewise, the Netherlands, along with Belgium and Germany, show high reliance on transboundary water. All Scandinavian countries, Germany and the Benelux countries are ranked high in the people pathway (due to openness to asylum seekers and migrants) and the trade pathway.

Figure 33 compares EU Member States with other countries with regards to risks from within each country's border (horizontal axis) and TCI (vertical axis). The figure shows that EU Member States are relatively less vulnerable to territorial climate risks (they are all to the left in the figure). However, EU Member States span a relatively large part of the vertical dimension. In fact, there are only a few countries globally that score higher on the TCI index than those EU Member States that are most exposed to TCI (Netherlands, Luxembourg, Belgium).

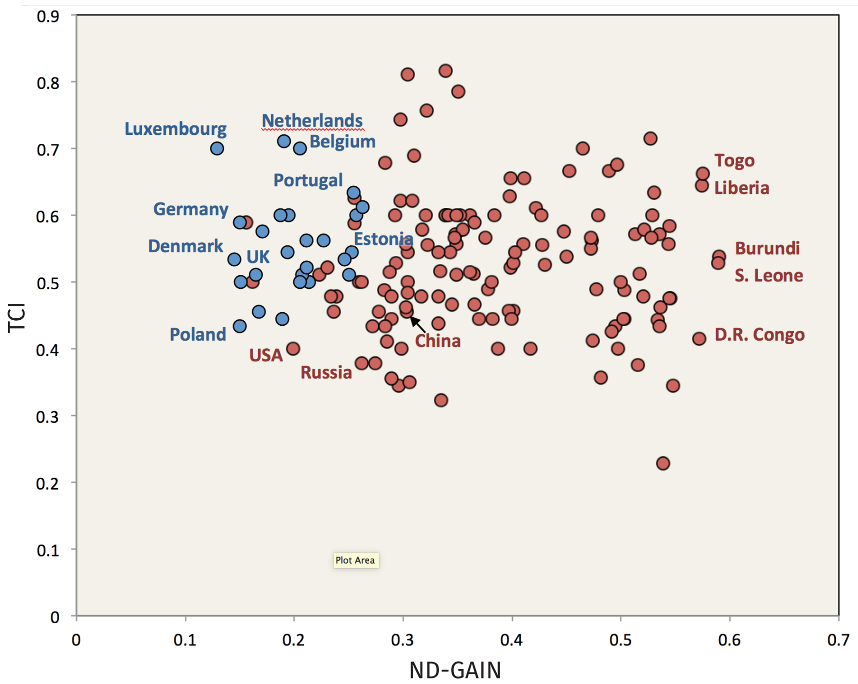

Figure 33. Comparing EU member states (blue circles) with non-member countries (red circles) with regards to climate risks emerging from within each country's borders (as measured by the ND-GAIN index; horizontal axis) and transnational climate impacts (as measured by the TCI index; vertical axis). Nine EU Member States are highlighted as well as a selection of key countries (China, Russia, US) and most territorially vulnerable countries (Togo, Liberia, Burundi, Sierra Leone, DR Congo).

Climate risks that emerge within a country's borders is only half the story, countries are also affected by impacts beyond its borders. Hitherto, almost all adaptation planning in Europe fails to incorporate these transnational climate impacts. Furthermore, although climate change is integrated into the EU's broader development cooperation portfolio, transnational climate impacts are generally not accounted for in national adaptation planning in partner countries.

Transnational Climate Impacts – Insights from a Case Study on Cross-border Climate-Induced Migration

Cross-border migration from Bangladesh to India is an example of South-South movements with a complex array of drivers and outcomes that nuance assumptions about direct causal links between climate change and migration. While much of this migration has been associated with the 1971 Bangladeshi Liberation War and subsequent attacks against Hindu religious minorities (Kumar, 2009), several studies project that climate change will lead to increased flows of migrants from Bangladesh to India (Homer-Dixon, 1994; Myers, 2002; Alam, 2003). Water scarcity in some areas has been linked to cross-border movements, while sudden disasters have been associated with higher migration flows to India in the hope of securing some additional resources to cope with the disaster (Panel Discussion on Management of Water Resources and Water Security: The Case of the Ganges-Brahmaputra-Meghna, 2010 cited by McAdams et al., 2010; Poncelet, 2010).

Drawing on fieldwork which took place in October 2016 in communities situated in cyclone-affected areas in Southwest Bangladesh and West Bengal, this HELIX case study examines the nature of cross-border migration from climate-vulnerable areas in Bangladesh into India, and to what extent it may offer some insight into transnational climate impacts in Europe.

The study reveals a plethora of drivers that reflect Bangladesh's complicated relationship with religion and identifies politics, lack of job availability, the development gap between the two neighbouring countries, insufficient adaptation mechanisms, as well as cross-border family networks. The way that these drivers interact is complicated. For instance, while climate hazards are not always the first reason people give for migrating, they are often referred to as the main reasons for livelihood uncertainty, which drives family members to migrate over the short- and long-term from affected areas in order to restore income losses or to improve their access to diverse livelihood options and better living standards. Furthermore, lack of trust in the government due to inadequate early warning signals and unequal distribution of post-disaster assistance, often mingle with pre-existing politico-religious tensions, which only exacerbate feelings of insecurity, and thus fuels the urge to leave the country permanently.

The study also yielded several counterintuitive results. While cross-border migration is often deemed unlikely for the poor, particularly when resources are strained in the aftermath of a disaster (Henry et al., 2004; Findley, 1994), migration can be facilitated by transnational familial and social networks (McAdam and Saul, 2010). Furthermore, few participants who had already made the move to India had any intention to migrate again further into India, preferring to remain in the West Bengal area where there were no language barriers, and where their social networks could ensure their integration. This contradicts common assumptions that environmental migration eventually leads to intercontinental migration in Europe (Population Council, 2011). Furthermore, many households refused to migrate despite having suffered major losses after repeated catastrophes. Often, climate hazards had become built into their worldview, and reconstructing their houses built into their lifestyle.

Policy implications

The extension of the impacts and adaptation agenda to also include transnational climate impacts has policy implications for the EU and its Member States with regard to transmissions of climate risks between Member States as well as with regard to impacts outside the Union that are transmitted to the EU.

Adaptation in the EU: The EU plays an important role in coordinating adaptation strategies and enhancing solidarity when climate impacts transcend individual state borders, to ensure that the most vulnerable regions are able to adapt. This is not adequately addressed in the EU's key policy instrument for climate adaptation, the EU Adaptation Strategy (DG CLIMA), which ensures funding for cross-border coastal and flood management. This strategy is currently undergoing an evaluation which should take into account the Paris Agreement and "the direct and indirect effects of climate change outside the European Union". This evaluation should include the latest science with regard to analysis and assess transnational climate impacts which are directly relevant to EU, national and corporate adaptation frameworks, and should be incorporated into their strategies and plans. The European Environment Agency's recent report on impacts and vulnerability in Europe (EEA, 2016) has a section devoted to 'Europe's vulnerability to climate change impacts outside Europe'. This report could provide valuable input to the evaluation of the Adaptation Strategy.

International development and cooperation: The European Union is the largest international aid donor, collectively (the Commission (DG DEVCO) and its Member States) providing more than half of global official development assistance, and the EU is also the world's largest contributor of climate finance to developing countries. In its efforts to integrate climate action into partner countries' development planning, the EU should explicitly design programmes and finance mechanisms to address transnational climate impacts, including via multi-country projects. By framing climate risks as a common risk between countries the EU could play a facilitating role to enhance international cooperation.

Trade: Being the world's largest importer and exporter trade is vital for economic growth in the EU, and the EU is, therefore, active in strengthening the multilateral trading system, as exemplified by its active role in WTO, the new trade agreement with Canada (CETA) and ongoing negotiations on TTIP. However, coherency between the social and environmental values of the EU trade policy have not been met in the latter two trade deals, and sustainable development must therefore be better defined in the agreements if such deals are not to undermine the environmental integrity of signatory countries.

Foreign Policy: Climate change is addressed as one key risk in the EU Global Strategy. The strategy recognises the potential for climate change and environmental degradation to exacerbate potential conflict, as well as to be an important driver of migration across Europe's borders. A key focus of the Common Security and Defence Policy (CDSP) has been on deploying military missions to climate-stressed regions of the world, thereby demonstrating an approach aimed at disaster response rather than on preparedness. Capacity for impact-based early warning systems for climate risks must be developed, while more comprehensive partnerships are sought between the various EU organisations and policies such as CSDP, ENP, DG CLIMA and DG DEVCO in order to implement climate action that holistically increases preparedness and improves resilience in developing countries.

Migration: The South Asia case study demonstrates the need for more policy collaboration between countries in the event of cross-border climate displacement. Concrete strategies and dedicated funding, along with more systematic inclusion of modules on climate change should be included in migration profiles and mobility dialogues in the GAMM (Blocher, 2016). Equally, adaptation and migration can be discussed within the scope of mobility partnerships of the ENP Clima East and Clima South MPs. Any such discussion should situate climate change migration within a constellation of drivers, risks, vulnerabilities, opportunities and corresponding coping strategies that all affect the choices of climate-stressed people. The EU Global Strategy 2016, which puts emphasis on preventing the root causes of displacement, can be funnelled into various adaptation and development projects to improve the resilience of environmentally vulnerable countries. In showcasing counterintuitive examples of the way people move, the Bangladeshi case study challenges common causal assumptions that have thus far guided policy on border securitisation. This demands more careful policy analysis which acknowledges the less direct trajectories of climate-induced migration, thereby more accurately responding to practices on the ground.

Policy insights

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Key messages

Policy Insights

- Either avoiding or exceeding 2°C global warming could pose unprecedented challenges as well as new opportunities for societal transformation. Innovative approaches in science and policy may be required. Integrated strategies for these new social-ecological conditions could be achieved, and ensured in the long run, by linking climate-oriented, practical, systemic solutions to sustainable development.

- Sustainable solutions are those that are able to overcome multiple trade-offs between ecological integrity and socio-economic goals in ways which can be turned into positive synergies. Clusters of sustainable solutions can be identified, tested and implemented by integrating multiple forms of knowledge and values in concrete places following transformative visions of the kind of world in which we want to live.

- Conventional and additive approaches focusing on single sectors, scales or either adaptation or mitigation without considering long-term sustainable development may not be enough to cope with the mounting risks and challenges of high-end climate change. Innovative approaches entail combining multiple systems of solutions that not only solve present problems but also learn how to transform current systems arrangements so as to prevent them occurring again.

- Conventional policy appraisal methods are designed for relatively short-term, well-understood policy choices in single sectors and are not feasible for transformative approaches combining multiple systems of solutions. They face severe limitations for assessing the impact of very long-term decisions about adaption and mitigation in the face of large climate risks.

Key scientific findings

Cross-sectoral implications of high-end climate change

Earlier sections of this report provide evidence of the strong interconnectedness of social-environmental systems and the ways that these interlinkages can exacerbate the potential negative impacts of HECC. However, such interconnectedness also creates new opportunities for the implementation of innovative systems of solutions. For example, some clusters of systems especially relevant in the context of HECC are the following:

Trade – Food - Agriculture systems cluster: In the case of European agriculture, model results suggest that trading patterns and the willingness of land managers to adopt novel land-uses are extremely important in allowing adaptation to changing climatic or socio-economic conditions. This means that non-climatic factors, including consumer behaviour, will substantially determine both food supply levels and the scope for maintaining other necessary or desired land-uses in Europe under HECC. Furthermore, the spatial distribution of impacts on arable and livestock systems will depend on the relative impacts of future change on agricultural and forest profitability and the availability of irrigation water. Supporting change in consumer patterns, e.g. towards organic, less meat or more locally produced products, can also support new job creation, reduce GHG emissions and transform agriculture in ways that reduces harmful effects on biophysical systems.

Water - Land-use – Biodiversity Conservation cluster: There is significant potential for integrated solutions to address the cross-sectoral interactions between hydrological systems, land-use planning and biodiversity conservation. HECC will have impacts on water availability and quality in many catchments. The projected increase in severity and duration of droughts, especially for the southern part of Europe, will have implications for various sectors, including agriculture, forest and ecosystems, domestic supply, power supply and tourism. The scope for successful biodiversity and ecosystem conservation under HECC depends upon the interplay of climate and human land-use. Even if conservation is prioritised, the need for basic resources such as food, water, energy and timber means that natural areas may suffer loss of extent and coherence regardless of any direct climate impacts. Cross-sectoral interactions can arise through poorly implemented land-use changes. Similarly, any change in protected areas may have significant land-use implications. Coping with growing water stress and loss of biodiversity resulting from HECC will involve implementation of integrated river basin and ecosystem conservation strategies to find and harmonise positive synergies between land-use and nature-based solutions policies.

Urban – Health - Mobility systems cluster: Most people in Europe live in cities and to a large extent the health of European citizens depends on the quality of their urban environments. HECC could increase the severity and duration of heat waves, trigger longer periods of thermal inversion in cities leading to worsening air quality and posing new challenges to fossil fuel-based urban mobility. However, urban centres are also where most innovations related to transformative economic arrangements and smart technologies in the use of energy and resources are taking place. New work-place arrangements reducing unnecessary travel and making new forms of a sharing economy possible could further foster such innovations and lead to multiple co-benefits in improved health, green wealth creation and more climate-resilient styles of urban living.

Cross-scale implications of high-end climate change

Findings in this report show systems' linkages across spatial and temporal scales. For example, with reference to spatial scale and biodiversity protection, it is shown that for some scenarios, protecting areas to prevent intensification and preserve habitats in one location may lead to knock-on effects on other habitats elsewhere. The spatial linkages are also shown via indirect effects of climate change: in an increasingly globalized world, no country is fully insulated from the impacts of climate change outside its borders. To date, almost all adaptation planning in Europe fails to incorporate these transnational climate impacts. Transnational climate interlinkages also need to be addressed in international development policies and can trigger novel forms of global cooperation.

Temporal scale interlinkages are addressed in the example of coastal adaptation and ecosystems restoration, where decisions have a long life-time, long-term impact and are often costly. Exploring adaptation pathways and integrating them into resilient mitigation policies can help decision makers to take the right decisions at the right time without path-dependency. In the face of uncertainty, managers and planners are urged to develop robust adaptive plans capable of anticipating and preventing multiple negative irreversible consequences. Such plans consist of combinations of both short-term actions and long-term options. These plans should be successful for a range of possible futures and flexible enough to adapt to changing conditions and "expected surprises".

The limits of adaptation and mitigation under high-end scenarios

Beyond the 2°C global warming threshold, conventional solutions to adaptation and mitigation may well prove not to be enough. Transformative solutions aimed at implementing radically different institutional arrangements, searching for synergies between adaptation and mitigation and linking them to sustainable development become increasingly central. In this regard, transformation has been defined as 'the altering of the fundamental attributes of a system (including value systems; regulatory, legislative, or bureaucratic regimes; financial institutions; and technological or biological systems)' (IPCC, 2012). Since such transformation will likely face institutional challenges, innovative solutions to HECC must actively contribute to the transformability of the overall system. Transformative solutions should potentially allow for a new system to emerge when the existing system is no longer feasible. Figure 34 shows the conventional approaches to climate change mitigation and adaptation compared to the approaches of transformative mitigation and adaptation, which are closer to a sustainable development approach, and transformation, in which transformative mitigation and adaptation are integrated within a sustainable development paradigm.

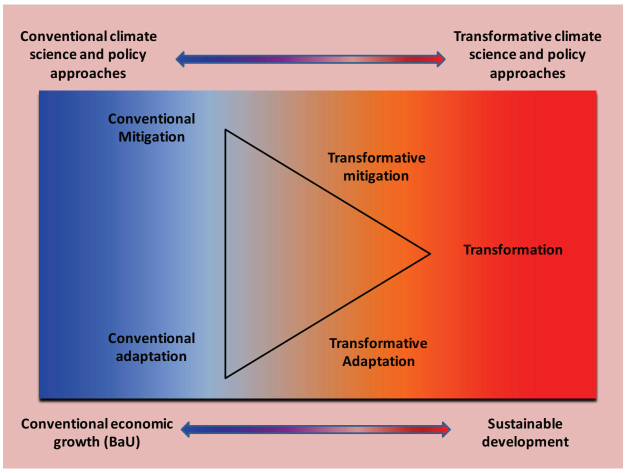

Figure 34. Conventional versus Transformative Climate Science and Policy Approaches, from IMPRESSIONS.

Conventional economic appraisal methods, such as cost-benefit analysis, face severe limitations in the context of high-end scenarios and transformative solutions (Tinch et al., 2015). These methods depend on the ability to estimate future market and non-market values, requiring monetary expressions of all costs and benefits. Estimates are grounded in the assumption that expressions of preferences, made under present incomes, technologies, social structures and behavioural options, are stable and reliable indicators of welfare. This is not the case for long-term projections and transformative solutions that differ significantly from the current situation, due to non-linearity and threshold effects, fundamental data gaps and imperfect knowledge of ecological and social-economic relationships. Standard methods of assessing uncertainty, based on the theory of rational choice under uncertainty and the calculation of expected values, cannot be employed for extreme, long-term scenarios for which the probability distributions of future events are unknown and unstable.

Integrated solutions to high-end climate change

Single-issue, sectoral, target-based or incremental solutions alone are unlikely to deliver the kinds of large-scale profound transformations needed to ensure quality of life in the long run and cope with the kinds of challenges posed by HECC. Sustainable solutions are those that are able to overcome multiple trade-offs between ecological integrity and socio-economic goals in ways that can be turned into positive synergies. The most innovative and robust solutions to HECC are those which contribute to the building the appropriate system conditions and agent capacities for charting alternative development pathways aligned with sustainability.

Solutions must not only solve present problems but also help transforming current systems arrangements so as to prevent them occurring in the future. Furthermore, innovative solutions need to be able to identify and explore the governing principles and mechanisms driving systems dynamics. Many of these principles and mechanisms have a normative and regulatory content and thus lie within the domain of public policy. Therefore, integrating systems of solutions requires making explicit the kinds of policy principles and normative criteria which are to be used to guide and manage complex social-ecological systems. Some of these principles are already well known, such as the polluter-pays-principle, albeit barely applied fully. A 'moral compass', that helps to the redistribute global rights and responsibilities in the face of HECC and engage citizens under broad principles of justice, precaution and intergenerational equity, amongst others, is needed.

Another important element in understanding the transformative potential for solutions is how they affect the future dynamics of the system through feedback loops. Humans not only influence, they are influenced by fluctuations in ecological systems, which in turn have multiple reactions and often unexpected effects on the organisation of human societies. There are many feedback loops between different levels and domains of society, as well as in the various parts of ecosystems that are not fully understood. Institutions ignoring these may not be able to engage in the necessary adaptive and learning behaviours and actions to prevent the further degradation of ecosystems.

Synergies can occur between various responses to climate change. They can occur between adaptation actions in the same sector (e.g. urban trees can reduce runoff and urban heat island effects) or in a different sector (Berry et al., 2015). They can also occur between adaptation and mitigation. Obviously, at the global scale, mitigation reduces the amount of adaptation that is required. It also reduces the speed of warming and therefore facilitates natural adaptation by ecosystems. Conversely, there are adaptation measures that also could provide mitigation benefits. For example, expansion of forests and overall ecosystems restoration can increase carbon storage, as can wetland/coastal habitat creation providing they are managed to avoid potential increases greenhouse gas emissions.

Alongside the need for integrated solutions, there is a need for innovative methods to evaluate adaptation and mitigation policies under scenarios of high climate sensitivity (Tinch et al., 2015). For long-term, uncertain impacts, presenting policy appraisal in simple expected value terms risks giving a spurious and ultimately unhelpful, even dangerous, illusion of confidence or certainty. Approaches focusing on robustness and associated indicators of capacities for action are more appropriate and informative. There are many candidate indicators relating to broad definitions of wealth and welfare, capabilities and capacities, and specific outcomes such as mortality or vulnerability indicators. Options for using these indicators include maximin criteria, setting vulnerability thresholds, or linking policy appraisal closely to the modelling of the evolution of capacities over time. Especially in the context of highly unpredictable and potentially severe future damages, there is less interest in 'optimal' policy and more interest in aiding a process of reflection about the possible consequences of climate change and possible robust adaptation options for dealing with them, maintaining flexibility, building up capacities for action at multiple scales, and encouraging the emergence of transformative solutions.

Examples of innovative integrated solutions

As indicated above, there is a need to combine mitigation with adaptation and sustainable development. Solutions to HECC include any integrated combination of policy measures, technological innovations, economic and information instruments, as well as other different types of conscious actions, either at the individual or collective level, which successfully addresses both the problems of climate change and unsustainability in concrete contexts of action. Thus, solutions are always situated solutions, taken on by specific agents in particular places in a dynamic learning mode.

Climate change, with its plethora of multiple feedbacks and global reach, entails looking at many different kinds of solutions. The kinds of transformation needed as a result of HECC may not be achieved by any single kind of solution. Instead, to reach a tipping point in positive transformation to tackle HECC what may be required is to package and unleash the cumulative, multiplicative and synergetic effects of different kinds of solutions.

Solutions in the context of HECC require an enormous level of cooperation and social innovation. To overcome trade-offs between present and future interests, between individual and

Different kinds of solutions

As a general tenet, the development of systemic solutions for HECC entails moving the traditional science and policy focus of attention from the question about 'what is the problem' towards 'who is the solution'. Innovative strategies will require the integration of multiple kinds of strategies:

Economic and financial measures

Innovative forms of investment and finance are crucial in mobilising the resources necessary for mitigation, adaptation and sustainable development. Carbon pricing and the recycling of revenues derived from the Emission Trade System are major potential sources for such investments, but direct private investments and small loans could also play a decisive role. Mobilising and linking large global investments funds to long-term sustainable climate strategies is one of the main and most urgent challenges to be addressed. Applying the Polluter Pays Principle in full could have tremendous positive effects in transforming key sectors, such as energy, trade, health, mobility or food production, although rebound effects and multiple trade-offs must also be considered.

Policy and regulatory measures

In the context of HECC, policy measures are needed to provide the legal enabling environment to support transformations in a way that adaptation and mitigation can be linked sustainable development. Policy and regulatory measures are crucial because unsustainability is to a large extent an institutional challenge and institutions need laws to secure changes in the long term. Defining the most suitable legal context to confront HECC cannot, however, be left to any single level of governance, but demands an interplay of many actors working at national, subnational and international levels using a long-term vision of positive change.

Organisational and corporate strategies

Organisational strategies and solutions relate to the design and implementation of systems to meet concrete objectives, either with private or public purposes. Organisational capacities are potentially the most important capacities to cope with HECC. The emergence of the networked society has created new opportunities to organise time, work and leisure in ways that allow improvement of quality of life and reduced resource use. Numerous examples of innovative ways to organise production, consumption and distribution of goods and services also make it possible to create value and alleviate poverty in a sustainable low-carbon way, by using new forms of finance, micro-credits, sharing and collaborative economy or even time-banks.

Technologies

Green infrastructure leads to a more efficient and productive use of resources. It minimizes environmental impacts while maximizing benefits to society and the economy. Green buildings are not just more energy efficient; they are also comfortable, healthier, and sustainable. Green building certification systems and other initiatives can encourage efficient use of resources while making a significant impact on mitigating greenhouse gases. An important recent development is 'nature-based' solutions (e.g. green roofs, new forms of retaining water or dealing with coastal erosion). Large-scale geo-engineering to address HECC should be considered with caution, because if the ultimate causes of unsustainability remain untouched, geoengineering could become more part of problem than of the solutions.

Behavioural, education and cultural strategies

Human and institutional behaviour are central to the successful implementation of policy. Cultural changes lie at the root of systemic changes and entail changes in perception, aesthetics and preferences. Examples of behavioural changes include new lifestyles, vegetarianism, reducing individual carbon and energy footprints, and reducing waste. With new sustainability values, individuals tend to support social arrangements that take into account the rights of future generations, respect and integrate the value of the non-human world and preserve the quality and integrity of the global commons. However, while changing individual behaviours and preferences lies at the root of any transformative change at the macro level, it is not clear that the effects of any particular individual change in behaviour will have the expected results. The aggregate effects of individual action are very complex and poorly understood phenomena.

collective concerns, and between ecological integrity and human welfare, new forms of networked leadership and transformative capacities are needed. Transformative strategies and solutions to HECC demand profound changes in institutions, in the redistribution of rights and responsibilities in the use of the global commons, in worldviews and information systems as well as in the very fundamental modes of the economy. Innovative solutions to HECC thus entail fundamental modifications in social-ecological interactions, which can only emerge as a process of social learning (Tabara et al., 2017). Experimentation, openness, reflection, and strong collaboration are central tenets for the emergence of such new forms of science-policy-citizens interactions.

At this stage it would be naïve, if not incredibly pretentious, to believe that we already know the most suitable, effective and fair solutions or strategies to cope with HECC. However, innovative solutions are already being combined and implemented by front-runners all over the world in a synergetic mode – as win-win solutions, no-regrets options, or integrated planning interventions. These can be carefully scrutinised and communicated to help understand their feasibility and scalability in other contexts. In addition, new tools and methods being explored, for example, in the IMPRESSIONS project (Tabara et al., 2017), may support building capacities for action and also help to identify the kinds of actors required to deal with HECC and sustainable development.

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Despite the Paris Agreement, global greenhouse gas emissions remain on track to warm the climate by more than 2°C above pre-industrial levels. Adaptation to such "high-end" climate change, and decisions on action to avoid it, require robust assessments of the associated risks. In a complex, interdependent world, these need to go beyond assessing individual impacts of gradual change. Risk assessments and adaptation planning must consider interactions between various impacts, the potential for passing tipping points, and the need to cope with radical rather than gradual change. It is vital that decision-makers have access to reliable scientific information on these uncertain, but potentially high-risk, scenarios of the future, so that they can develop and implement effective adaptation and mitigation plans and policies.

IMPRESSIONS, HELIX and RISES-AM were contracted by the European Commission to advance understanding of the consequences of high-end climate change, involving temperature increases above 2°C. The three projects have assessed climate change impacts, vulnerability and possible adaptation interventions across a range of policy sectors, in order to help decision-makers apply such knowledge within integrated adaptation strategies. This policy booklet describes our research findings and understanding which is emerging on these issues and our reflections on the implications for policy and decision-making.

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