IMPRESSIONS Final Report

Integrated solutions to address high levels of climate change

IMPRESSIONS – Impacts and Risks from High-End Scenarios: Strategies for Innovative Solutions (www.impressions-project.eu)

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Executive summary

We are not yet on track to meet the Paris Agreement climate change target of keeping global average temperature rise within 2°C above pre-industrial levels. Current greenhouse gas emission trends point to much more substantial warming, with possible increases of 4°C or more in the long-term. The IMPRESSIONS project researched what a future above 2°C could look like, which we define as "high-end climate change". The project also assessed what decisions we can take to help reduce the impacts of such high-end climate change. However, climate change isn't the only problem the world faces; we live in a world with poverty, poor health, water shortages, a lack of food security, land degradation, resource depletion, mounting social inequalities and weak governance systems. These global problems are all closely interlinked and our current solutions for tackling them tend to be over-simplistic.

To better understand this complexity, the IMPRESSIONS project co-developed four scenarios with stakeholders and applied these to five case studies: Hungary, Scotland, Iberia, Europe as a whole and Central Asia. The four scenarios were: a future in which there is a commitment to achieve sustainable development (SSP1); a future where increasing demand for resources leads to conflict within and between countries (SSP3); a future of high inequality where global and political elites dominate (SSP4); and a future of fossil-fuelled development (SSP5). Each socio-economic scenario (based on the Shared Socio-economic Pathways, SSPs) was paired with the most relevant climate change scenario (based on the Intergovernmental Panel on Climate Change Representative Concentration Pathways, RCPs). The two fossil-fuel dependent scenarios (SSP3 and SSP5) were paired with a high warming scenario (RCP8.5) where temperatures in Europe increase by approximately 4-6°C by 2100. The two lower carbon scenarios (SSP1 and SSP4) were paired with a lower warming scenario (RCP4.5) where temperatures in Europe increase by approximately 2-3°C by 2100. On current trends we are heading somewhere between these two scenarios, though closer to RCP8.5.

IMPRESSIONS modelled the possible impacts of these scenarios using integrated models that take account of the complex interactions, synergies and trade-offs between different sectors (agriculture, forestry, water, biodiversity, urban, health). Benefits in some regions and sectors, such as increasing forest productivity in northern Europe, are offset by detrimental effects in others, such as severe water scarcity, heat stress and loss of productivity in southern Europe and parts of central and eastern Europe, and widespread flood damage. Finally, adaptation and mitigation pathways were generated with stakeholders to inform integrated and transformative solutions. Three common cross-scale pathways for climate action were identified: (i) shifting to sustainable lifestyles through a cultural change in ways of living, commuting, producing, purchasing and learning for a reflexive and sustainability-oriented society; (ii) governance for sustainability and climate resilience that is democratic, flexible, cooperative and transparent; (iii) and new forms of integrated and sustainable resource management that address water, energy, food, land-use and biodiversity holistically, to create synergies and alleviate trade-offs. Analysis of the adaptation and mitigation pathways shows that beyond the 2°C threshold, conventional solutions to adaptation and mitigation may 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 important.

The stakeholder-led approach of IMPRESSIONS ensured that the research was driven by the priorities of decision-makers from key economic and social sectors so that significant co-learning was achieved. This has enabled decision-makers to identify robust, innovative and effective solutions for addressing high-end climate change. The approach also highlights the societal and policy innovations and supports the transformations needed to realise synergies between adaptation and mitigation and achieve a sustainable green economy.

1. Introduction

1.1. Project context

The Paris Agreement states that climate change should be limited to "well below" 2°C and that countries should strive to limit temperature rise even further, to 1.5°C. However, it has been shown that achieving the 2°C target will require more emissions reductions than currently pledged. Thus, without early and drastic emissions reductions, high-end climate scenarios (where the temperature increase is above 2°C and could rise as high as 4-6°C) are very plausible despite international agreements. However, there are few studies that simultaneously assess their potential impacts, the ability of adaptation options to reduce vulnerabilities, and their potential synergies and trade-offs with mitigation. Thus, it is vital that decision-makers have access to reliable scientific information on these uncertain, but potentially high-risk, scenarios of the future to inform integrated adaptation and mitigation planning.

The consequences of climate change are highly complex and challenging to predict, even more so when coupled with rapid and uncertain socio-economic change, such as population growth, technological change, international cooperation and shifting institutional and governance systems. When preparing for climate change we need to think carefully about the consequences of different choices we face. Climate change and our reaction to it will have impacts on economies, human wellbeing and other global challenges as stipulated in the United Nations Sustainable Development Goals.

1.2. Objectives

The IMPRESSIONS (Impacts and Risks from High-End Scenarios: Strategies for Innovative Solutions) project aimed to provide a scientifically robust and policy-relevant understanding of the nature and scale of more extreme and long-term consequences of climate change, and support the use of this knowledge by decision-makers working on adaptation, mitigation and sustainable development.

It was guided by the following objectives:

- To establish decision-maker needs for enhancing current approaches to climate change policies and actions;
- To develop an integrated set of high-end climate and more extreme socio-economic scenarios;
- To apply these scenarios to a wide range of models to explore impacts and adaptation, focusing on the analysis of multi-scale and cross-sectoral synergies and trade-offs;
- To co-create a suite of adaptation and mitigation pathways and assess the adequacy of adaptive capacity for implementation of the pathways;
- To develop recommendations on integrated and potentially transformative solutions that help society plan for the long-term in the context of high levels of climate change.

To achieve these objectives five case studies were carried out covering multiple scales: (i) in two municipalities in Hungary (Szekszárd and Veszprém); (ii) at the national scale in Scotland; (iii) for a transboundary river basin in Iberia (the Tagus); (iv) at the continental scale for Europe; and (v) in an international case study that explored interactions between Europe, Central Asia, Russia and China under high-end climate change.

1.3. Methodology

The IMPRESSIONS approach was implemented in the five case studies in a number of steps (as illustrated schematically in Figure 1):

Step 1: In-depth interviews were undertaken with stakeholders to understand what tools and knowledge decision-makers need in order to make robust and effective decisions on adaptation and mitigation in the face of highly uncertain scientific information.

Step 2: Participatory workshops, complemented by online engagement with stakeholders, were organised to describe potential future changes in socio-economic drivers (e.g. economic, demographic, technological, social and political). These were combined with climate change scenarios according to the magnitude of greenhouse gas emissions in the socio-economic assumptions. The socio-economic and climate scenarios were based on the Intergovernmental Panel on Climate Change scenario framework of Shared Socio-economic Pathways (covering SSPs 1, 3, 4 and 5) and Representative Concentration Pathways (covering RCPs 4.5 and 8.5) to enable consistency and comparability across the different scales and contexts of the case studies. This led to a set of integrated scenarios about what the future might look like under high-end climate change.

Step 3: The scenarios were used to drive models to project future changes in impacts for different sectors of the economy, society and environment. A common multi-scale modelling framework was developed to analyse the complex interactions, synergies and trade-offs between different sectors such as agriculture, forestry, urban development and tourism as they compete for land, water and energy, and the resulting impacts on health and biodiversity. The models results were used to indicate whether the system as a whole was becoming more or less sustainable under each integrated scenario.

Step 4: Stakeholders were involved in co-creating a vision of a sustainable future for the case study for the year 2100. The visions describe people's aspirations for governance, energy, social equity, living and lifestyles, the environment and other factors essential to human well-being.

Step 5: Stakeholders worked with the project team to co-create a suite of harmonised adaptation, mitigation and transformation pathways that attempt to move society from the projected future impacts (from **step 3**) and towards the sustainability visions (from **step 4**). The pathways consist of several strategies (focused on people, nature, markets or technology), which describe bundles of actions that are specific activities carried out by one or multiple actors at a specific point in time.

Step 6: The effectiveness of the pathways was evaluated using the models and qualitative analyses to assess the extent to which the actions in the pathways moved selected vision indicators closer to the vision of a sustainable future. The results of this evaluation were fed back into the stakeholder engagement process to highlight where the pathways could be strengthened.

Step 7: This resulted in a set of pathways that work in all scenarios, with different emphases for each case study, to achieve the vision of a sustainable future. In each case study, combinations of transformative solutions accelerate progress towards the vision.

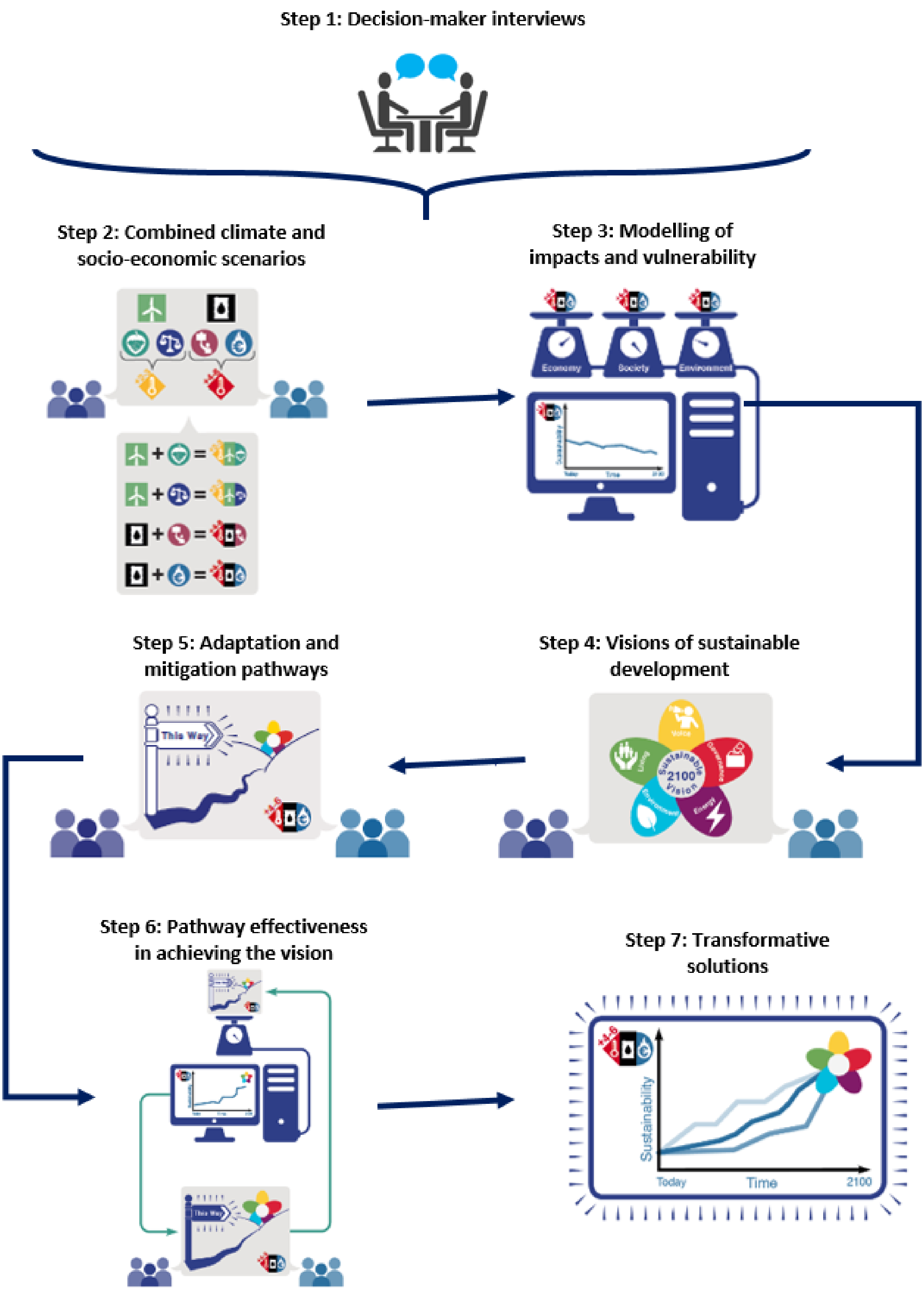


Figure 1: Schematic representation of the IMPRESSIONS methodology.

2. Main S & T results

2.1. Combined climate and socio-economic scenarios for Europe

The IMPRESSIONS project examined the implications for Europe of future changes in both climate and socio-economic drivers. Many natural and human systems are sensitive to changes in climate variables such as temperature, rainfall, wind and humidity (their averages as well as their extremes). Socio-economic factors determine the greenhouse gas emissions and land use changes that cause anthropogenic climate change, but also affect our exposure, vulnerability and capacity to adapt to these climate hazards.

The climate and socio-economic scenarios in IMPRESSIONS were based on a globally agreed set of pathways developed by the international research community for use in climate change assessments: the Representative Concentration Pathways (RCPs) and Shared Socioeconomic Pathways (SSPs). These were downscaled to a set of European scenarios, and then downscaled further to provide detailed scenarios for the case study areas of Iberia, Scotland, Hungary and Central Asia.

2.1.1. Global climate scenarios

The RCPs describe different ways in which atmospheric greenhouse gas and aerosol concentrations might change up to the year 2100, with extended versions to the year 2300. Concentrations are expressed according to their warming effect on the atmosphere ('radiative forcing') in Watts per square metre (Wm^{-2}) by 2100 relative to pre-industrial levels (defined as 1850-1900). Temperature estimates are derived from an ensemble of climate models run by different research groups, so that each pathway spans a range of possible values. Three RCPs were used in IMPRESSIONS (Figure 2):

- **RCP8.5** assumes that no further mitigation policies are adopted after the year 2005. The average projected global temperature rise in 2100 is +4.3°C relative to pre-industrial times, though five out of 39 climate models project more than +6°C. Even if emissions were subsequently to fall to zero by 2250, average global warming is projected to reach +8.6°C by 2300 (within a range of +3 to +12°C). RCP8.5 was adopted as the highest climate change scenario in IMPRESSIONS.

- **RCP4.5** requires strong mitigation action to limit the average global temperature rise to 2.4°C in 2100, continuing to rise slowly to reach +3.1°C by 2300. It was adopted in IMPRESSIONS as the main alternative scenario to RCP8.5, displaying global warming on average somewhat above the 2°C policy target.

- **RCP2.6** requires very strong climate mitigation action, with emissions peaking in 2020 and falling to zero by 2100, resulting in an average temperature rise of 1.6°C by 2100, and declining temperatures after that. Few downscaled climate projections were available for Europe at the time of scenario selection so RCP2.6 was not included as a core scenario in IMPRESSIONS, though it was used in the European case study to compare against high-end scenarios after the Paris Agreement was signed.

Following the Paris agreement, countries pledged to reduce their emissions by promising a set of 'Nationally Determined Contributions' (NDCs). Some of these were promised unconditionally, and some were conditional on actions by other countries. The pledges only guarantee emission reductions up to 2030, so it is not possible to estimate what impact they would have in 2100. However, although the NDCs will certainly reduce emissions below the RCP8.5 trajectory, they would not put us in line with RCP6.0 (the emissions scenario between RCP8.5 and RCP4.5), let alone deliver the Paris target.

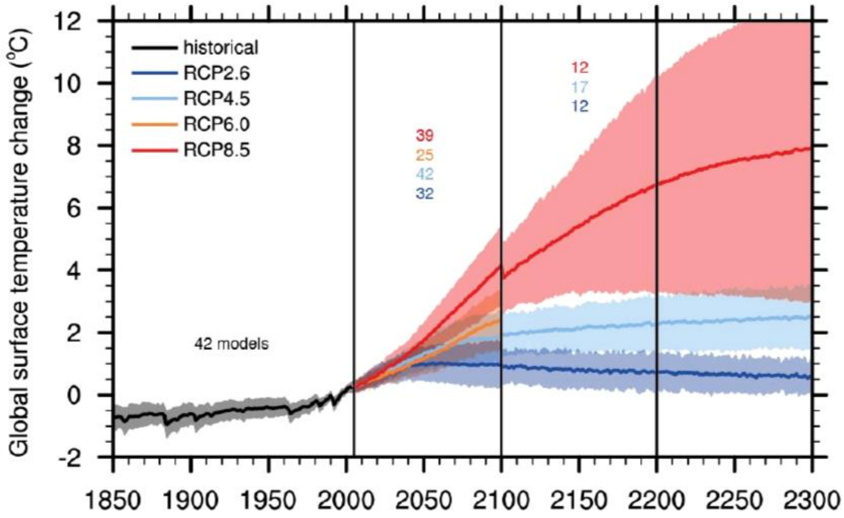


Figure 2: Projected global annual mean surface air temperature anomalies (relative to 1986-2005; add 0.6°C to compare to pre-industrial). Solid lines are multi-model means (coloured numbers show how many models were used) and shading shows the likely range (5th to 95th percentile). [IPCC, 2013, based on CMIP5]

2.1.2. European climate scenarios

For Europe, a subset of ten climate models was selected to span the range from the very low-end of the RCP2.6 projections to the high-end of the RCP8.5 projections. Although there are some differences, the models agree that southern Europe will become hotter and drier under climate change, while northern Europe becomes warmer and wetter (Figures 3 and 4). In a +4°C world (RCP8.5), extreme long-term drought conditions are expected to occur more frequently throughout southern Spain, southern Italy, southern Greece and Cyprus.

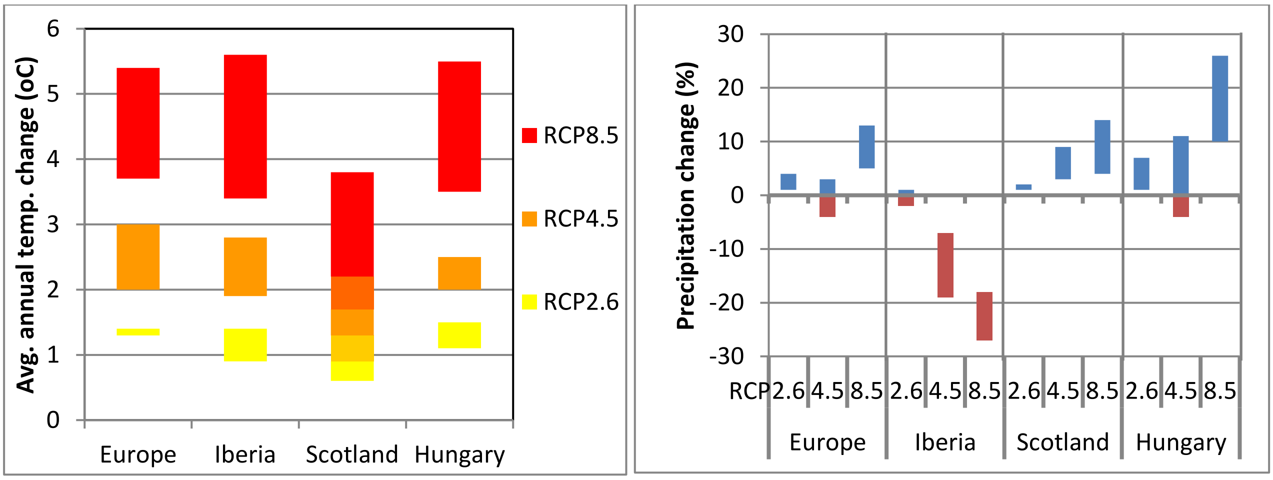


Figure 3: Change in annual average temperature (left) and precipitation (right) in 2071-2100 relative to 1961-1990 for the RCP2.6, RCP4.5 and RCP8.5 climate change scenarios in IMPRESSIONS showing the range for different climate models.

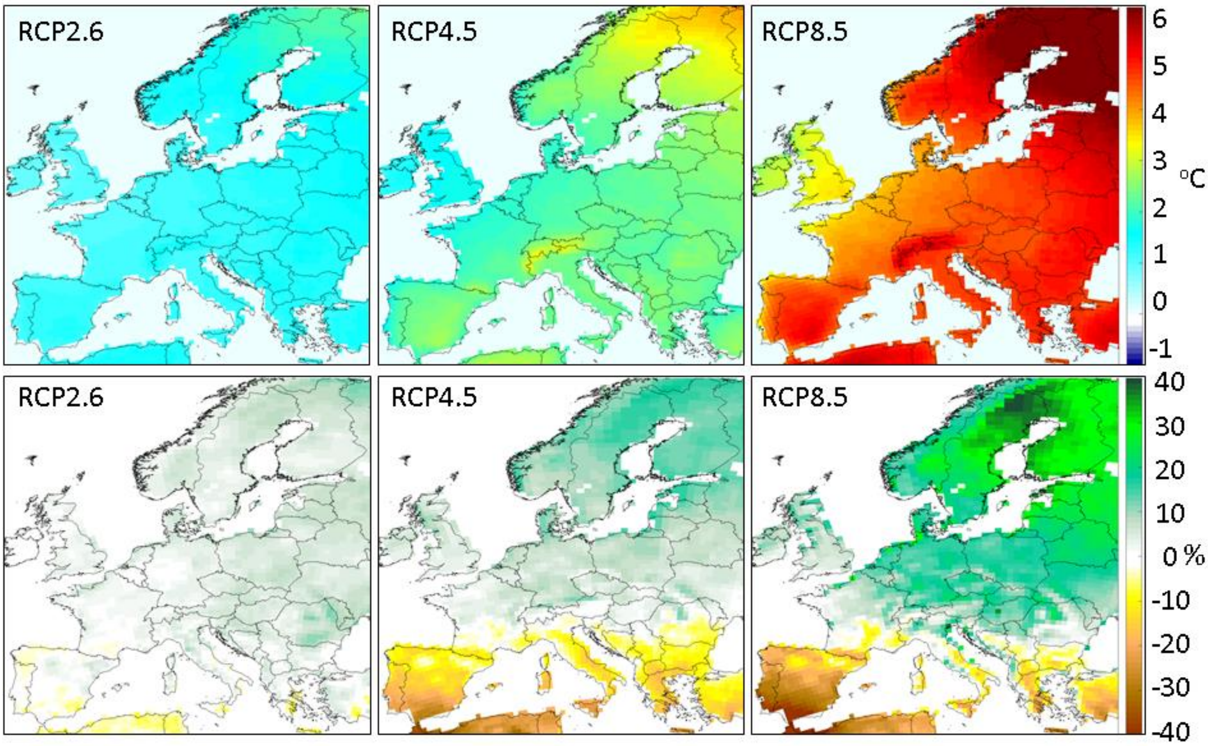


Figure 4: Projections of changes in average annual temperature (top) and precipitation (bottom) for RCP2.6, RCP4.5 and RCP8.5 from 1961-1990 to 2071-2100 (mean outputs from the IMPRESSIONS subset of climate models).

2.1.3. Socio-economic scenarios

The international research community has defined five global Shared Socioeconomic Pathways (SSPs 1 to 5), which seek to explore future development pathways with differing challenges to adaptation and mitigation. IMPRESSIONS worked with stakeholders to create socio-economic scenarios based on four of these SSPs (omitting the 'middle of the road' SSP2). SSPs were created for Europe as a whole, and separate sets consistent with these European SSPs were created for each of the IMPRESSIONS case study areas (Hungary, Scotland, Iberia and Central Asia).

Each RCP was paired with the most relevant SSP. The two fossil-fuel dependent scenarios (SSP3 and SSP5) were paired with the higher warming scenario (RCP8.5), and two low carbon scenarios (SSP1 and SSP4) were paired with the lower warming scenario (RCP4.5).

The socio-economic scenarios determine how society might respond to climate change (Table 1). SSP1 represents a sustainable and co-operative society with a high capacity to adapt, and low vulnerability to food and water stress. Combined with lower warming, this presents fewer challenges for adaptation. In SSP3, social and political fragmentation combined with high climate change (RCP8.5) poses challenges for adaptation. In SSP4, even with lower warming (RCP4.5), high levels of inequality mean that only the elite can adapt effectively. SSP5 features heavy reliance on technological solutions, but with high climate change (RCP8.5) resulting from dependence on fossil fuels, parts of southern and eastern Europe collapse under severe environmental stress.

Table 1: Overview of the European socio-economic scenarios.

SSP	Global name	IMPRESSIONS name for Europe	Paired RCP	Description
SSP1	Sustainability - taking the green road	SSP1 - We are the world	**RCP4.5**	Low challenges to mitigation and adaptation. High development, low inequality. Sustainable and inclusive development, respecting environmental boundaries with emphasis on health, education and human wellbeing rather than growth at all costs.
SSP3	Regional rivalry – a rocky road	SSP3 - Icarus	**RCP8.5**	High challenges to mitigation and adaptation. Low development, high regional inequality. Nationalism, regional conflicts and low co-operation between regions. Low technological innovation, resource-intensive consumption and environmental degradation.
SSP4	Inequality – a road divided.	SSP4 - Riders on the storm	**RCP4.5**	Low challenges to mitigation, high challenges to adaptation. Unequal development, high within-country inequality. Power and knowledge concentrate in a small international elite who invest in low-carbon energy. The rest of society is poorly paid and poorly educated; social unrest and conflict is high.
SSP5	Fossil fuelled development – taking the highway	SSP5 – Fossil fuelled development	**RCP8.5**	High challenges to mitigation, low challenges to adaptation. High development, low inequality. Reliance on competitive global markets and participatory societies to produce rapid technological development, which underpins investment in human capital (health and education). High fossil fuel consumption and reliance on technology (e.g. geoengineering) to fix problems.

2.2. Modelling of impacts and vulnerability

A wide range of different models were used to explore the impacts of high-end climate change (based on the combined RCP and SSP scenarios) on agriculture, forestry, biodiversity, water resources, flooding, urban development and human health. The models were implemented within a multi-scale modelling framework, capable of combining many different simulations to explore the impacts of high-end climate change on multiple sectors at different geographic scales. The modelling framework also considered interactions between different sectors as they compete for resources such as land, water and energy. The models were applied at global, European, national and sub-national scales, and where possible they take account of interactions across scales, such as how trade flows at the global level define the level of food imports to Europe. Results of the modelling are described by policy sector in the following sections.

The modelling framework has enabled the exploration of synergies and trade-offs between different adaptation and mitigation actions (see Section 2.3). For example, a possible synergy is the potential for tree-planting to alleviate flooding as well as storing carbon. A possible trade-off is between reducing food imports and protecting European forests and biodiversity from large-scale agricultural expansion as more food is produced within Europe. It is in helping to understand such complex relationships that the IMPRESSIONS modelling framework stands apart from conventional approaches.

2.2.1. Impacts and vulnerability for the agricultural sector

Climate impacts vary dramatically across Europe, with southern Europe becoming hotter and drier, while northern Europe becomes warmer and wetter. If we meet the 1.5°C target (RCP2.6), impacts will be limited – for example annual average precipitation would decrease by less than 10% in the worst affected regions. However in a +4°C world (RCP8.5), extreme long-term drought conditions are expected to occur throughout southern Europe.

These increases in drought severity, water scarcity and heat stress are projected to cause increased crop stress and failure in parts of central and southern Europe, especially in the Mediterranean. Heat stress is likely to increase for livestock and poultry, reducing milk yields, egg production and weight gain. In northern Europe, in contrast, agricultural productivity could increase, boosted by warmer temperatures, a longer growing season and possibly a CO_2 fertilisation effect, if appropriate adaptation is implemented. As a result of these changes, agricultural systems are expected to shift northwards: arable farming may increasingly concentrate in the north-east while intensive livestock farming shifts to the north-west.

The pattern of change will be strongly influenced by socio-economic factors (Figure 5). For example, in a sustainability-focused scenario (SSP1) with reduced food imports and less use of agrochemical inputs, potential yields are assumed to decrease by 20%. Combined with climate, this leads to arable land expanding from 12% of land area today to 33% in the 2080s, at the expense of forests and unmanaged land. In the resource-intensive SSP5 scenario, potential crop yields are assumed to increase by 89% due to technological improvements (an optimistic assumption) and also food imports increase, so that the area needed for arable crops shrinks to only 3% of land area.

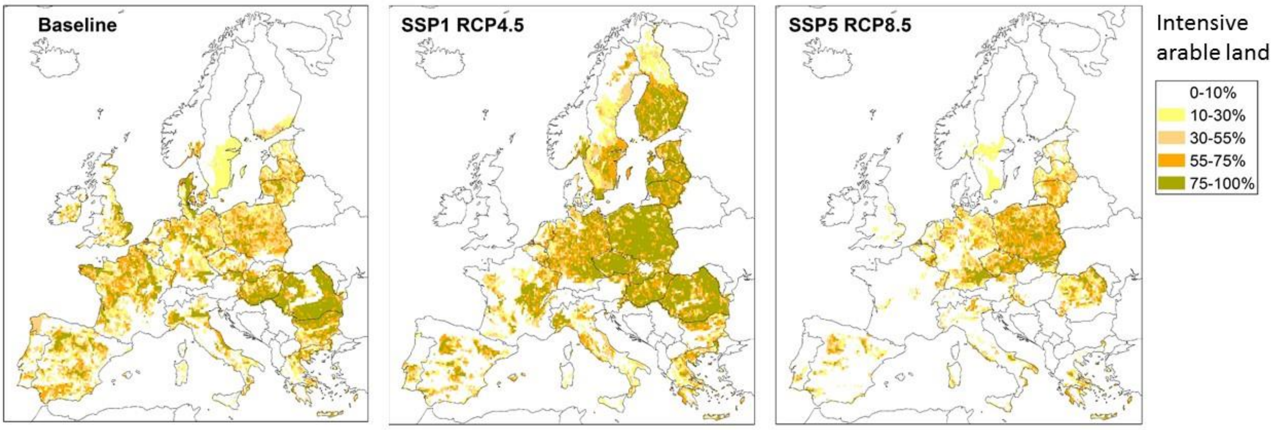


Figure 5: Simulated distribution of intensive arable crops (percent of grid cell) for baseline (present day) and two 2080s scenarios: low-input farming with reduced food imports (SSP1 x RCP4.5) and high-input farming with higher imports (SSP5 x RCP8.5).

Caution is needed in interpreting these projections because a number of important potential factors are not included in the crop yield and land use models. Firstly, these projections assume that farmers make decisions based on long-term profitability – in reality, there would be major socio-economic impacts associated with such dramatic shifts in land use, and considerable inertia to change. Secondly, as the climate warms, increased use of water for irrigation and in other sectors (energy, domestic, industrial) leads to severe water stress (water use > 40% of available resources) in all river basins in southern Europe and many in north-western Europe, which may lead to greater limits on the availability of water for irrigation than those simulated. However, under SSP1 greater efforts to improve water use efficiency in all sectors reduce the pressure on water resources compared to SSP5 (Figure 6). Finally, whilst warmer and wetter conditions could also increase the spread of pests and diseases, posing high risks for scenarios such as SSP5 where crop production is concentrated in a small area of Europe, the effects of pests are not included in the crop model (Figure 7).

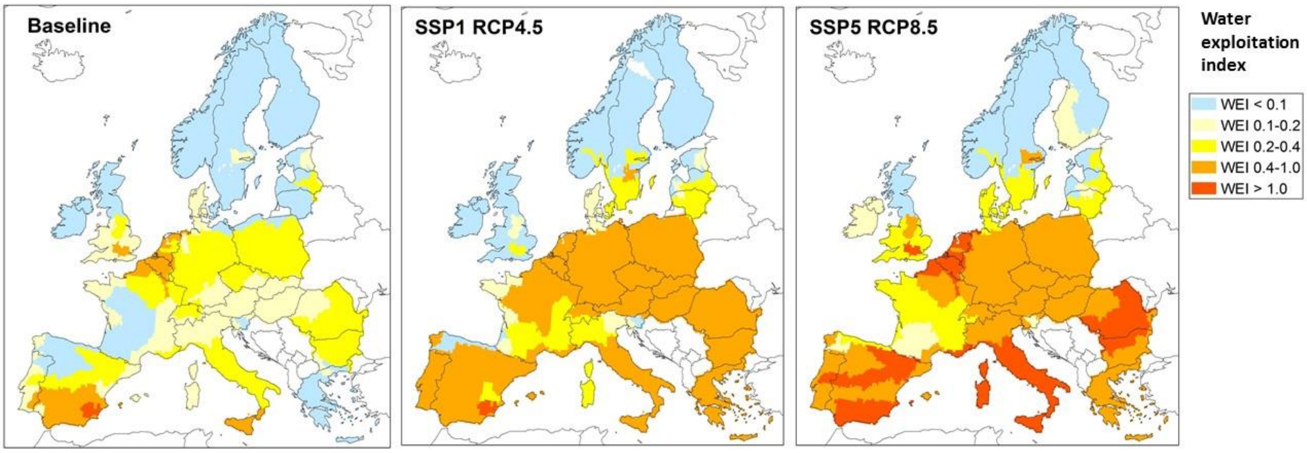


Figure 6: Water exploitation index (ratio of water demand to water availability) for baseline (present day) and two 2080s scenarios: SSP1 x RCP4.5 and SSP5 x RCP8.5.

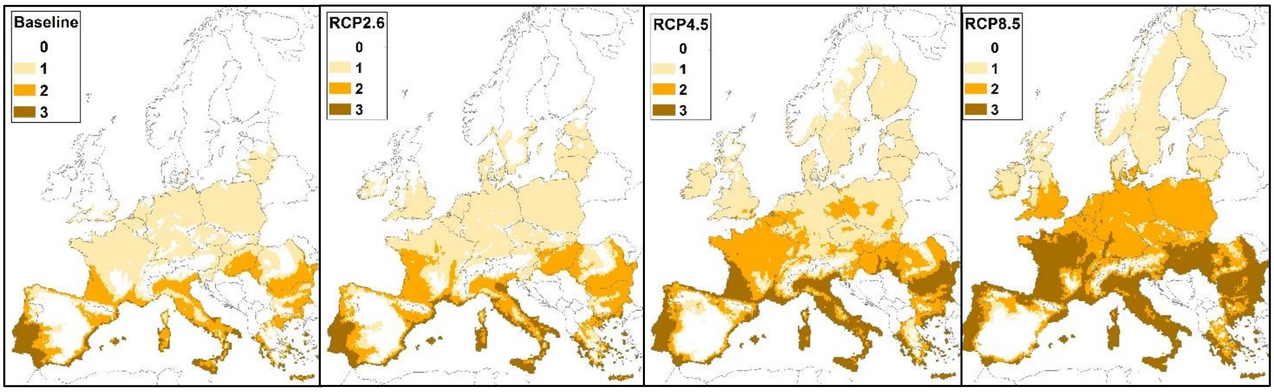


Figure 7: Spread of the European Corn Borer (*Ostrinia nubilalis*) northwards with increasing climate change. Number of generations per year under (left to right) baseline (current conditions) and RCP2.6, RCP4.5 and RCP8.5 in the 2080s.

Pollinators are expected to lose suitable habitat, especially in southern Europe (see section 2.2.3 on Biodiversity), which will reduce yields of many fruit, nut, oilseed, vegetable and flower crops. Around 10% of the economic value of food production in Europe is dependent on pollination. Loss of wild pollinators will force greater dependence on managed honeybees, with higher costs, lower pollination efficiency and less resilience to disease.

Europe is less vulnerable to climate change than many other world regions and food security is not expected to be threatened across the continent as a whole, unless imports from other countries are restricted. However, food security at a local level depends on access to reliable and affordable food, which is determined by the 'coping capacity' of society and the pattern of food production across Europe. In the SSP1 scenario, with strong equitable and participatory governance and high investment in health and education, as well as food production close to consumers, people are less vulnerable to food insecurity than in scenarios featuring conflict and inequality (SSP3 and SSP4), and where food has to be transported longer distances (SSP4 and SSP5) (Figure 8).

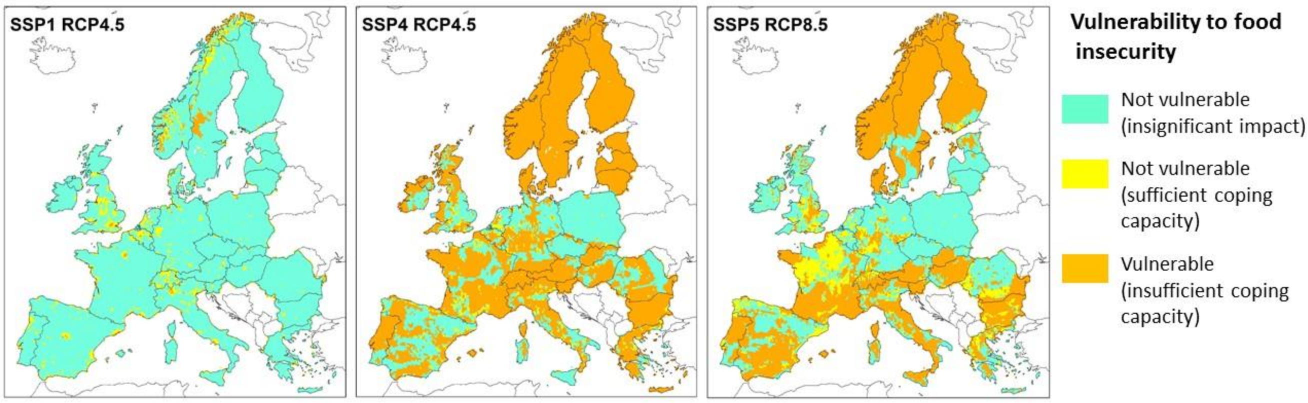


Figure 8: Vulnerability for food provision across Europe in the 2080s for SSP1 x RCP4.5 (highly distributed food system and good governance), SSP4 x RCP4.5 (high inequality and spatial mismatch between food production and demand) and SSP5 x RCP8.5 (spatial mismatch between food production and demand, and high climate change).

2.2.2. Impacts and vulnerability for the forestry sector

Climate models indicate lower rainfall and higher temperatures in southern Europe, leading to severe water scarcity. In the drought-prone Mediterranean basin and the dry continental interior, increased tree heat stress and transpiration are expected to lead to an average decrease in forest productivity of 1 to 4 m^3/ha/year (annual volume increment) by 2100, i.e. a decrease of 10% to 50% compared to the current climate (Figure 9). Climate change could even induce large-scale forest dieback. In Iberia, production of both cork and pine could cease completely by the 2080s under RCP8.5 (approximately 4-6^{o}C warming across Europe).

In contrast, forest productivity could increase in places where tree growth is currently limited by low temperatures, provided that precipitation remains adequate — typically in northern Europe and at high elevations. Either extant tree species such as Scots Pine or Norway Spruce will become more productive, or it will become possible to use tree species that have higher economic value than those being used today (e.g. oak).

CO_2 fertilization may have a positive effect on forest productivity and could therefore increase the positive effects of climate change or partly compensate its negative effects. However, this is uncertain as vegetation may acclimate to higher CO_2 concentrations, or other factors such as nutrients or water may become limiting. Pests and diseases such as ash dieback (*Hymenoscyphus fraxineus*) and the pine processionary moth (*Thaumetopoea pityocampa*) could spread as a result of climate change, but more research is needed to better understand these risks.

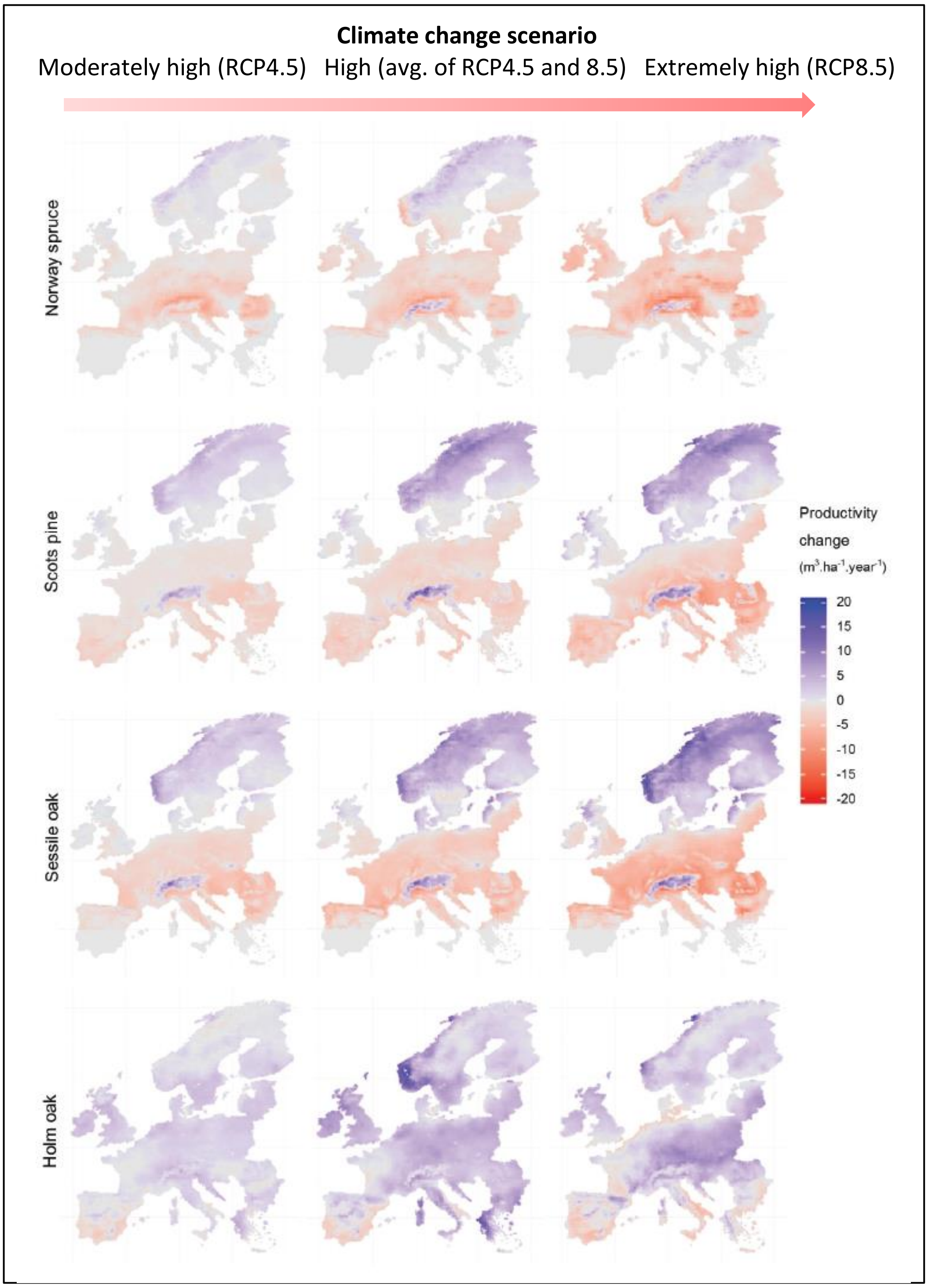


Figure 9: Change of productivity (annual volume increment) in 2070-2100 compared to baseline for two conifer (top) and two deciduous (bottom) species under increasing levels of climate change (left to right), based on the meta-ForClim model. The focus is on climate impacts only, so projections were made for homogeneous soil characteristics across Europe (water holding capacity set to 15cm to represent a mesic soil).

In addition, single extreme events (e.g. windthrow, heat waves) or series of events such as several drought years in a row could trigger widespread or species-specific tree mortality, including through increasing fire risk. Conversely, clusters of climatically favourable years could trigger forest expansion beyond current 'cold' treelines at high latitudes and high elevations. Invasive species such as the tree of heaven (*Ailanthus altissima*) or Japanese knotweed (*Fallopia japonica*) could also spread more rapidly. These impacts are not shown in Figure 9, which are therefore conservative estimates of climate impacts. Many ecosystem services provided by forests will be affected strongly by these changes.

Impacts depend on the species and on local conditions. Mediterranean tree species are projected to be severely affected by extreme drought events in the most southern parts of Europe, but their growth is likely to remain constant or even increase elsewhere. For example, Holm oak is already expanding northwards along the Atlantic coast of France. Norway spruce, which is widely used in plantations outside its natural range (e.g. at low elevation in Central Europe), is expected to exhibit strong negative impacts in most of Europe, except at the highest elevations. The more drought tolerant Scots pine will mostly exhibit negative impacts in the driest European regions, although its response may vary depending on local topography and soil conditions. In Scotland, for example, more detailed modelling shows that yields of the native Scots pine are projected to decrease at low elevations and in areas where the soil has low water-holding capacity, but to increase in the Highlands (Figure 10). In contrast, yields of some non-native species (i.e., Douglas fir and Sitka spruce) could increase (Figure 10). This has implications for the selection of tree species in Scottish reforestation policy, which in turn could affect biodiversity and landscapes.

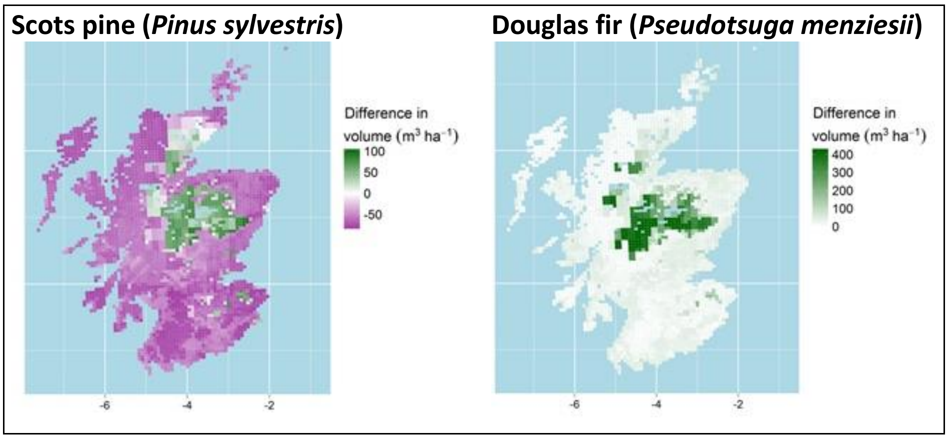


Figure 10: Difference in harvested volume under high climate change (average of RCP4.5 and RCP8.5 compared to baseline) using the ForClim model with local topography and soil conditions.

2.2.3. Impacts and vulnerability for the biodiversity sector

Under high levels of climate change, modelling projects lower rainfall and higher temperatures in southern Europe, leading to major habitat transformations and severe impacts on biodiversity. Species will be forced to migrate to areas with more suitable climates, generally involving a shift northwards or to higher altitudes. Survival will depend on the dispersal capabilities of the individual species, the availability of suitable habitats and the presence of connected habitat networks to enable migration. Whilst some species may be able to adapt and gain access to new 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.

Modelling shows that even under lower-end scenarios of climate change (RCP2.6), 13% of Europe loses over 10 species and 28% loses more than one species (Figure 11). Under RCP4.5, more than 10 species lose all suitable climate space and/or habitat in 28% of Europe, increasing to 36% under

RCP8.5. With high emissions scenarios the rate of climate change will exceed the ability of species to disperse to new habitats, even if suitable habitat and networks are available. If the climate stabilizes, species may be able to catch up, but models suggest that species with small climatic ranges would be at risk of extirpation if there is no remaining habitat in a suitable climate zone.

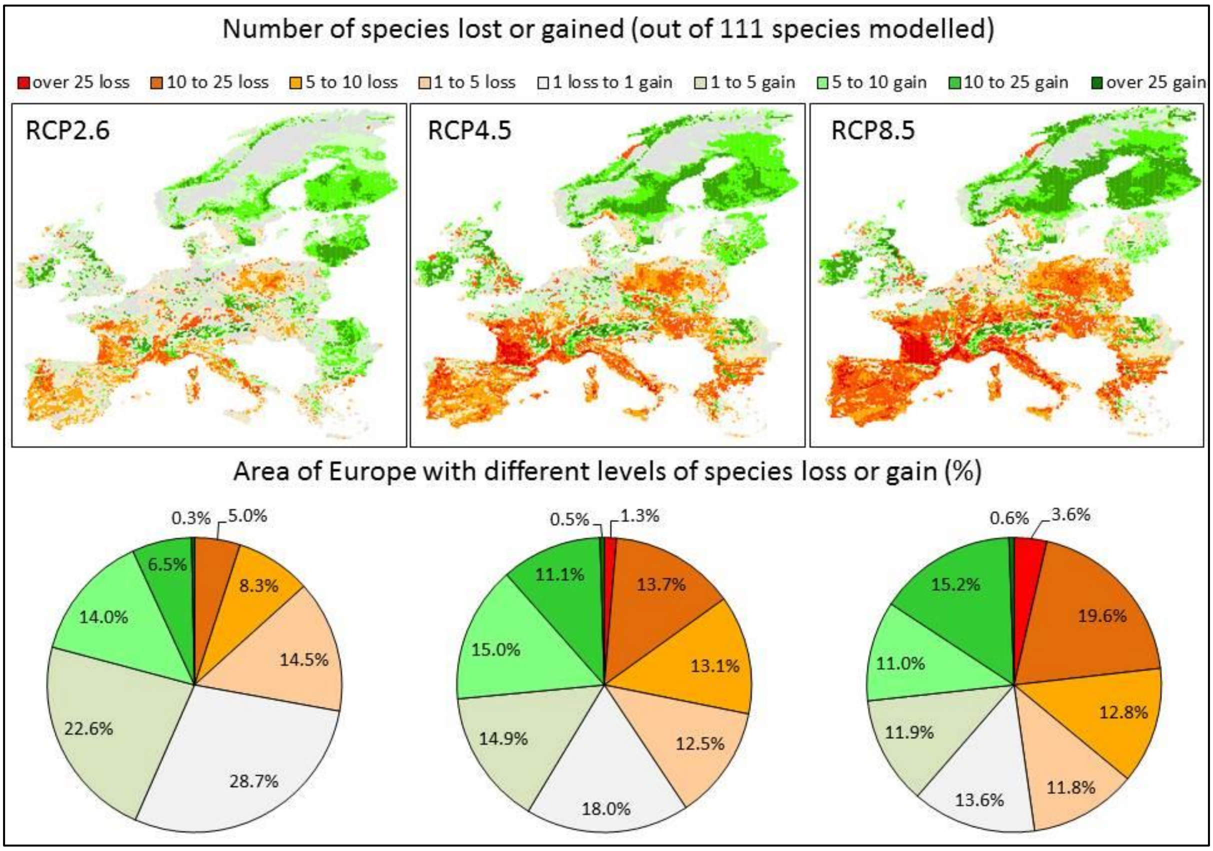
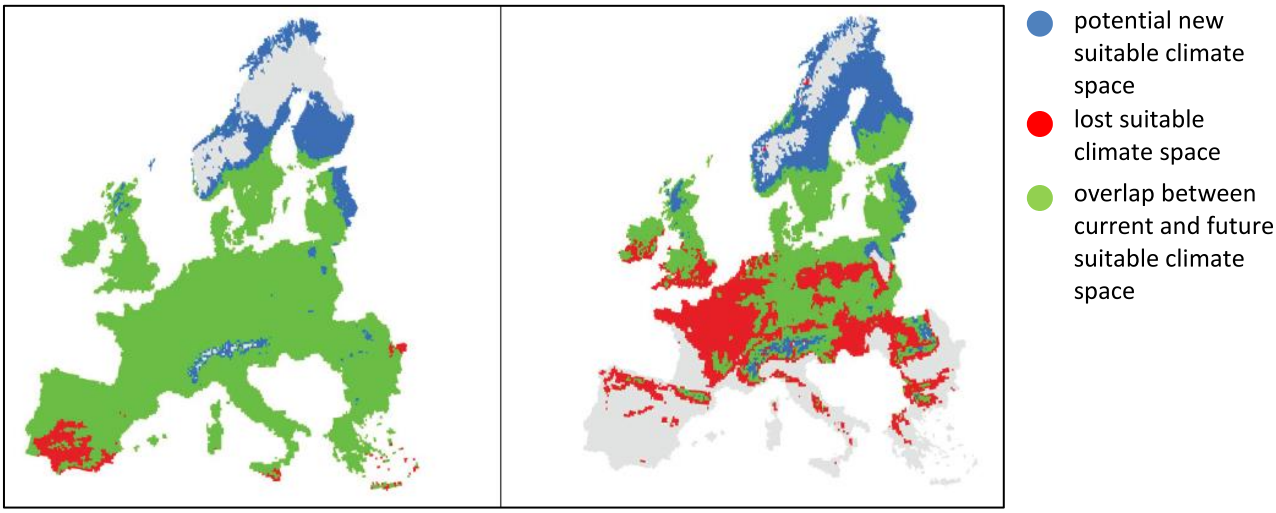


Figure 11: Change in climate and habitat suitability in the 2050s under increasing levels of climate change.

Socio-economic factors also have a major impact on biodiversity, as habitat for wildlife has to compete strongly with land needed for food production, commercial forestry, urban development and infrastructure. For example, a scenario with reduced food imports (SSP1) leads to agricultural expansion or intensification in Europe, at the expense of forests. However, a scenario with high levels of conflict and social instability (SSP3) leads to abandonment of agricultural land, with negative impacts on farmland species, but benefits for some grassland and woodland species.

Urban development also has a major impact. Under a resource-intensive scenario with high levels of urban sprawl (SSP5), sealed surfaces grow to cover 9% of Europe, compared to 4% in other scenarios. This would have further negative impacts on biodiversity (beyond those modelled in IMPRESSIONS) as habitats become increasingly fragmented, while infrastructure, such as roads, poses a major hazard to the movement of many animal species, reducing their ability to disperse.

The combined effects of these climate and socio-economic changes make a loss of biodiversity across Europe highly likely, with major consequences for the supply of ecosystem services. For the service of pollination, for example, modelling of nine key crop pollinator species projected that eight would lose suitable climate space in the Mediterranean region and, in some cases, in France, southern Britain, southern Ireland and Central Europe (Figure 12). The pollination service these species provide could be at risk unless they adapt to the new climate, or other (not modelled) species are more resilient, or new pollinator species become available. Conversely, a projected expansion of arable crops in southern Scandinavia is unlikely to be limited by the availability of pollinators providing that the pollinator species are able to adapt by moving with the climate.



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

Figure 12: Changes in suitable habitat and climate space for two pollinators due to high climate change (RCP8.5).

2.2.4. Impacts and vulnerability for the water sector: water supply and flooding

High levels of climate change are expected to dramatically alter rainfall patterns across Europe (see Figure 4). In southern Europe, significant decreases in annual rainfall are projected to lead to more frequent and prolonged droughts. At the same time, precipitation is projected to increase in northern Europe and parts of central Europe. Rainfall events could become more intense, flood risk will increase and lake and river levels could oscillate between low and high extremes.

Impacts and vulnerability depend strongly on socio-economic factors (Figure 13). Under an environmentally-focused scenario (SSP1), efficient water-use technologies and water-saving behaviour reduce pressure on water resources, and high human, social and natural capital increase coping capacity and thus reduce vulnerability to water stress. Under the resource-intensive SSP5 and the politically unstable SSP3, however, adapting to climate change is more challenging and severe vulnerability to water scarcity and flooding extends across much of Europe. If current emission trends continue (taking us close to the RCP8.5 climate scenario), virtually all river basins in southern Europe and many of those in north-western Europe will experience severe water stress (withdrawal to availability ratio >0.4), with adverse impacts on agriculture, forests, ecosystems, domestic supply, power supply and tourism.

Water scarcity will be a particular problem in the Iberian Peninsula, where there are already challenges for the management of transboundary water resources between Portugal and Spain. In the Tagus River Basin, winter flows are expected to fall by around 25% under RCP4.5 and 50% under RCP8.5, cutting hydropower production by approximately 45% and 50% in 2071-2100 (Figure 14). The region will be unable to meet competing demands for water for irrigation, urban use and canal transfers to the intensive horticulture region in south-eastern Spain, and the fulfilment of the Albufeira transboundary treaty between Portugal and Spain will probably become impossible by the end of the century. In the "green" SSP1 scenario with lower climate change and a 40% improvement in water use efficiency, the water shortages can be mitigated but only until mid-century. Droughts pose severe threats to the unique dry oak-grassland agroforestry systems known as "Dehesa" in Spain and "Montado" in Portugal, reducing the amount of forage available for livestock and leading to the end of cork production by the end of the century in RCP8.5.

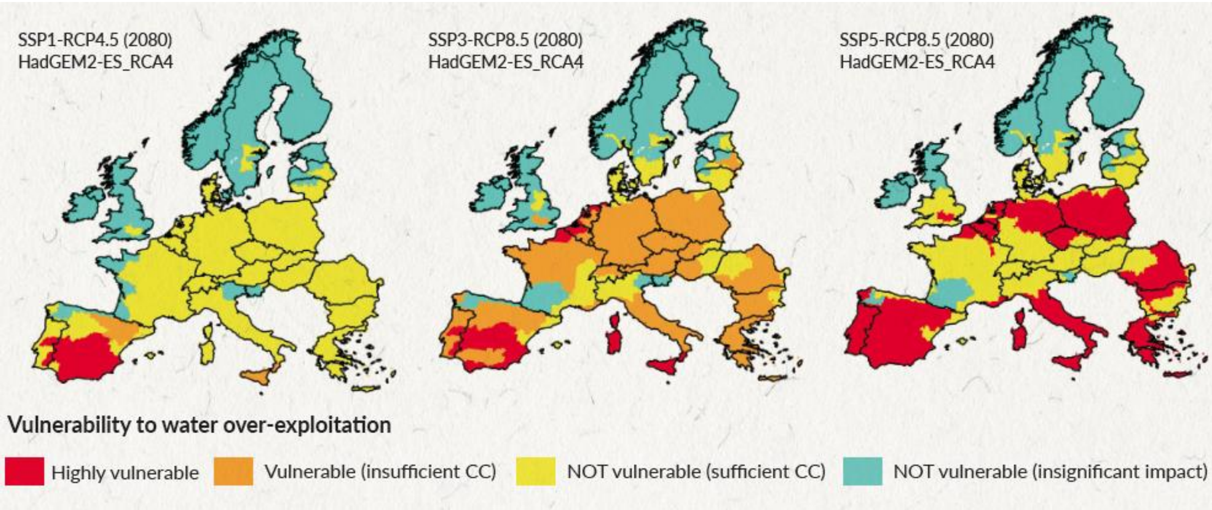


Figure 13: Vulnerability to water scarcity in European river basins for SSP1, SSP3 and SSP5 (left to right) in the 2080s (CC = coping capacity).

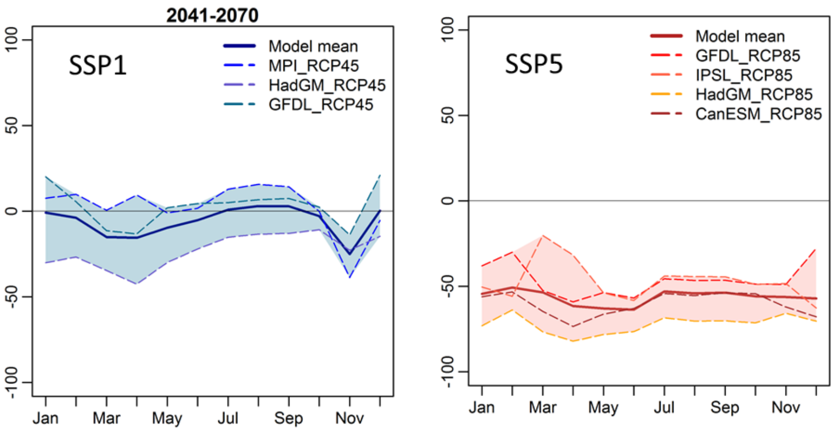
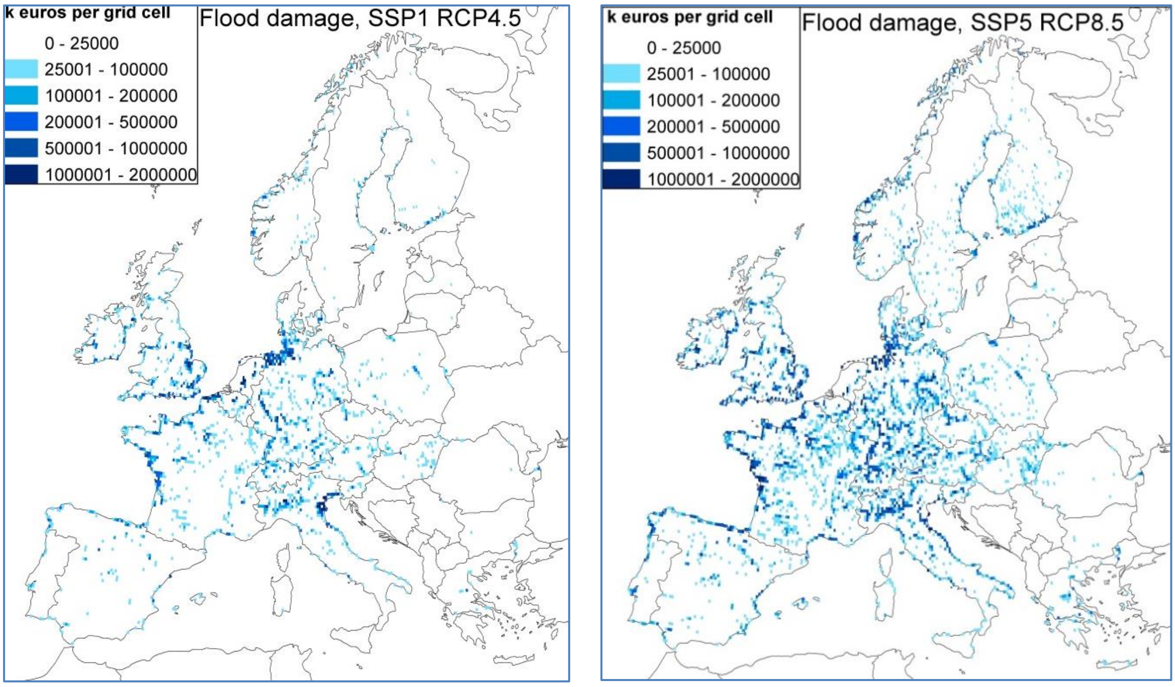


Figure 14: Change in discharge at the outlet of the Tagus river in 2071-2100 compared to 1981-2010 for a +2 to +3°C temperature rise with efficient water use (SSP1 x RCP4.5, left) and a resource-intensive scenario with higher climate change of +3.6 to +5.4°C (SSP5 x RCP8.5, right).

Similarly, flood damage is also highly dependent on socio-economic factors (Figure 15). Under SSP5, extensive urban sprawl creates large areas vulnerable to flooding. Estimated damage from a 1 in 100 year flood event grows from €78 billion today to €1800 billion in the 2080s, affecting an extra 15 million people. Under the more sustainable SSP1 scenario, compact urban development and lower climate change restricts the damage to around €490 billion.



Total damage ~€490 billion
~22 million people flooded

Total damage ~€1,800 billion
~32 million people flooded

Figure 15: Flood damage from a 1 in 100 year coastal and fluvial flood event in the 2080s (thousand euros per grid cell) for two scenario combinations: 2-3°C temperature rise with compact development (SSP1 x RCP4.5, left) and higher climate change (3.6-5.4°C) with urban sprawl (SSP5 x RCP8.5, right).

2.2.5. Impacts and vulnerability for urban development and human health

Urban development

IMPRESSIONS explored a range of future scenarios with contrasting patterns of urban development (Figure 16). In the 'fossil-fuelled development' scenario (SSP5), population growth of 47% coupled with lax planning policy, increasing wealth and preferences for single living and larger properties leads to a doubling in the area of artificial surfaces across Europe, from 4% of the land area today to 9% in 2100. The level of urban sprawl observed in this scenario – where only 18% of people live in cities - is a serious threat to Europe's sustainable urban agenda. It will encourage car dependency and thus elevate air pollution and carbon emissions; increase surface water flooding and the urban heat island effect; cause loss of ecosystem services and fragmentation of habitats for biodiversity; and could compete for land with agriculture and forestry, thus threatening local food and resource supply.

In contrast, in an environmentally aware scenario with zero population growth by 2100 (SSP1), society shifts towards more sustainable, compact development where 44% of people live in cities, with good access to public transport and other services, and artificial areas remain at their current level of 4%. In other scenarios, featuring high levels of inequality, weak planning and governance and low levels of environmental/social awareness (SSP3 and SSP4), poor urban planning leads to the emergence of urban ghettos with social challenges including unemployment, crime and segregation. These scenarios are likely to result in a low coping capacity and high vulnerability to climate change.

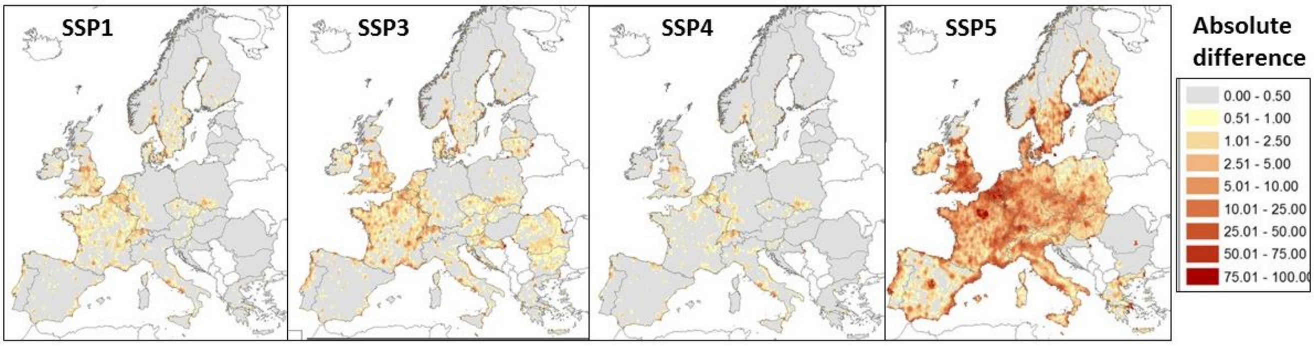


Figure 16: The projected change, from baseline to 2100, in % urban area in each grid cell under four different socio-economic scenarios characterised by sustainability (SSP1), regional conflict (SSP3), inequality (SSP4) and fossil-fuelled development (SSP5). Population stays the same in SSP1, falls by 38% in SSP3 and 22% in SSP4, and grows by 47% in SSP5.

Heat-related mortality

Climate change will increase the frequency and intensity of weather extremes. Spells of both hot and cold weather can be expected, where hot weather especially is associated with significant acute impacts on mortality and morbidity. On our current trajectory towards the RCP8.5 scenario (average increase of approximately 3.6 to 5.4°C in Europe by 2100), heat-related deaths in Europe could increase from around 25,000 per year in the baseline to over 100,000 by the 2050s, without adaptation (Figure 17). Impacts vary strongly across Europe, with southern and central Europe showing particularly large increases in heat-related mortality. Mortality is very dependent on age, and the number of elderly and very elderly is projected to increase dramatically after mid-century across large parts of Europe.

All populations are affected by high temperatures, but it is not known how quickly populations can adapt or the exact limits to adaptation. High ambient temperatures affect thermal comfort, productivity, energy use, and human health. 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. High temperatures are likely to affect the capacity to undertake activities outdoors - whether for leisure or employment.

Climate change could also trigger longer periods of thermal inversion in cities leading to worsening air quality. There will be health benefits from milder winters (reduced cold-related mortality or morbidity), however with additional risks due to more slippery conditions in northern parts of Europe.

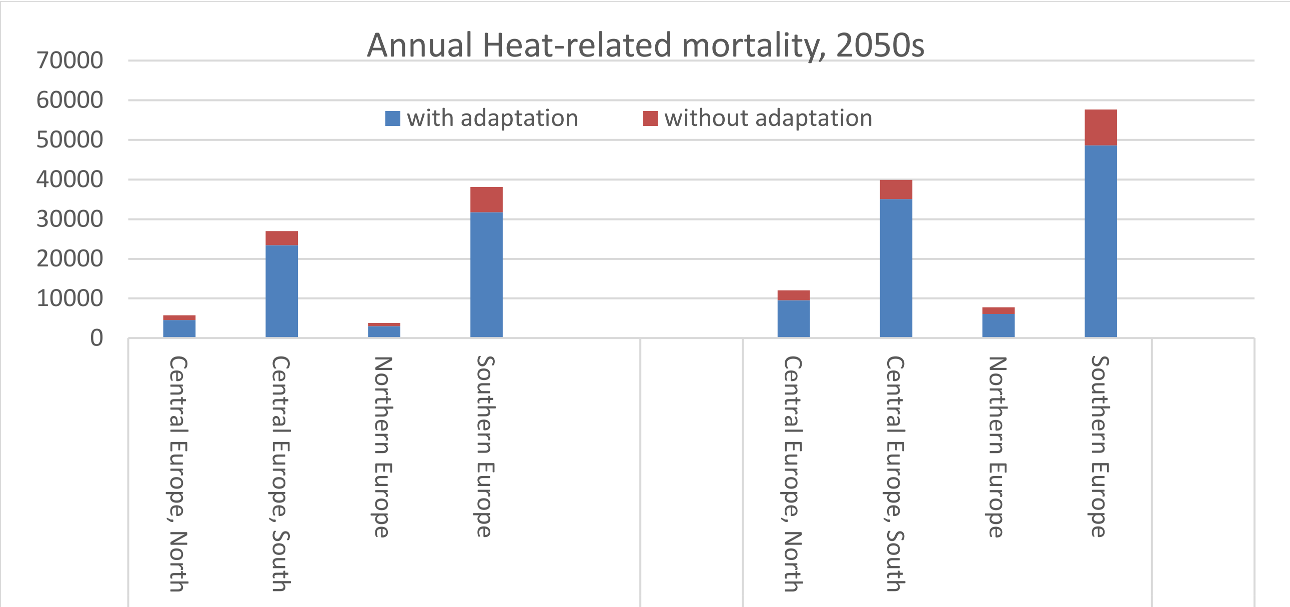


Figure 17: Future annual heat-related mortality in Europe, with and without adaptation for two scenarios: average temperature rise 2-3°C with sustainable development (RCP4.5 x SSP1) and average temperature rise of 3.6 to 5.4°C with urban sprawl (RCP8.5 x SSP5).

Lyme disease

Lyme disease is a potentially fatal infection spread by the bites of infected ticks, which has important implications for outdoor recreation. Cases of Lyme disease have risen recently due to greater exposure, as levels of outdoor activity have increased. Lyme disease risks are projected to increase in all scenarios in the two modelled areas – Scotland and Hungary — due to higher temperatures, which increase tick activity (Figure 18). It is likely that other European countries will also be affected.

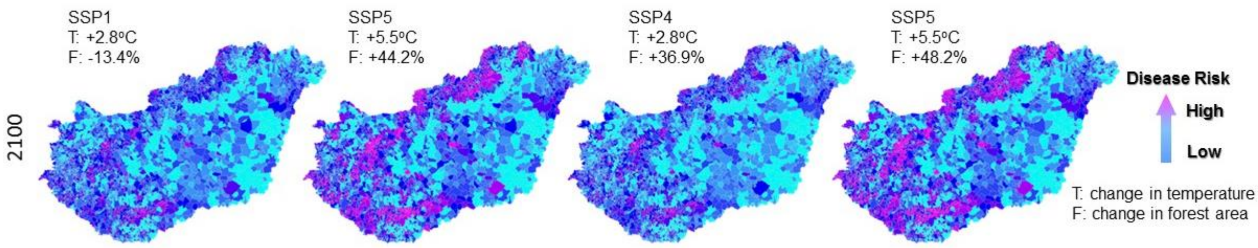


Figure 18: Risk of Lyme disease in Hungary based on the projected number of infected ticks per km^2 in four scenarios with lower (SSP1, SSP4) or higher (SSP3, SSP5) climate change (T) and different changes in forest area (F)

2.2.6. Impacts and vulnerability for economic and financial sectors

Models generally agree that if uncontrolled carbon emissions push average temperatures well above 2°C, there will be substantial damage to the economy. Climate change will directly affect labour productivity (e.g. via heat stress), capital stock (e.g. damage from extreme weather events) and industrial energy demand (e.g. through increased need for cooling), and impacts on sectors such as agriculture, forestry and energy will indirectly affect the European macro-economy. Uncertainty around key parameters (e.g. climate sensitivity and the damage function) leads to a wide range of potential outcomes, including catastrophic futures where a large share of economic production is lost. Using emissions scenarios equivalent to warming of around +5°C by 2100 (consistent with RCP8.5), the most optimistic estimates indicate an aggregate damage due to climate change of approximately 6% to 10% of global output (equating to around a decade of lost economic growth), while recent evaluations point to much higher impacts (a 40-80% loss in output). Based on this range, it seems likely that the activities of financial institutions such as banks, investment funds and insurance companies will also be strongly impacted by the economic losses arising in different sectors. Our financial system must be prepared to absorb potential 'extraordinary losses' (losses arising from unforeseeable events) from both climate-related physical events and climate policy implementation (for example via stranded high-carbon assets such as coal and oil reserves).

Standard integrated assessment models completely overlook frictions in the way the economy reacts to climate impacts (i.e. they assume that shocks are absorbed by price changes in perfectly competitive markets where production factors can adjust at any time). Many models also do not distinguish between the way in which different impacts might reduce the overall level of economic and financial activities. Building on the blossoming literature on complex system approaches to climate change, IMPRESSIONS developed a micro-level agent-based integrated assessment model (the DSK model) to study a variety of climate impacts in a realistic simulated economy, and to test possible corrective policies (see Section 3.1).

The DSK model has yielded major insights into the different ways in which climate change can affect the economy. It was used to study a reference scenario close to current trends (consistent with the RCP8.5 scenario), leading to a large temperature rise of +2.8 to 5.5ºC from the pre-industrial average. Economic growth was assumed to be high (around 3.2%) without climate damage, and, in the absence of policy interventions, the energy mix was assumed to be 80% fossil fuels. Three different types of climate damage were simulated: reduced labour productivity; increased energy use per unit output at the company level; and damage to the capital stock of firms (Figure 19). The impact of these climate damages on the economic activities of firms is likely to be an essential driver of the aggregate macro-economic outcome.

The model showed that in those economies where climate change reduces the productivity of workers (e.g. in sectors with a high share of outdoor work, such as agriculture and construction), the long run output growth rate is projected to decrease from 3.2% in the reference scenario (i.e. no climate damage) to reach negative values at the end of the century (Figure 19, left). When climate change results in increased energy intensity or damages the capital stock of firms, the impacts on growth are much lower. However, capital stock shocks incisively threaten the ability of firms to produce goods and services and, in turn, their very survival, increasing the bankruptcy rate (Figure 19, right). There are knock-on effects on the financial sector because bankruptcies imply that debt accumulated to financial institutions won't be fully repaid in the future. Such extraordinary losses will erode the equity value of banks and, hence, their solvency. These results show that economic and financial risks from high levels of climate change could vary across countries. Future research should uncover which countries are more exposed to certain types of shocks, rather than simply focusing on how much GDP might be reduced and how to counterbalance the welfare losses.

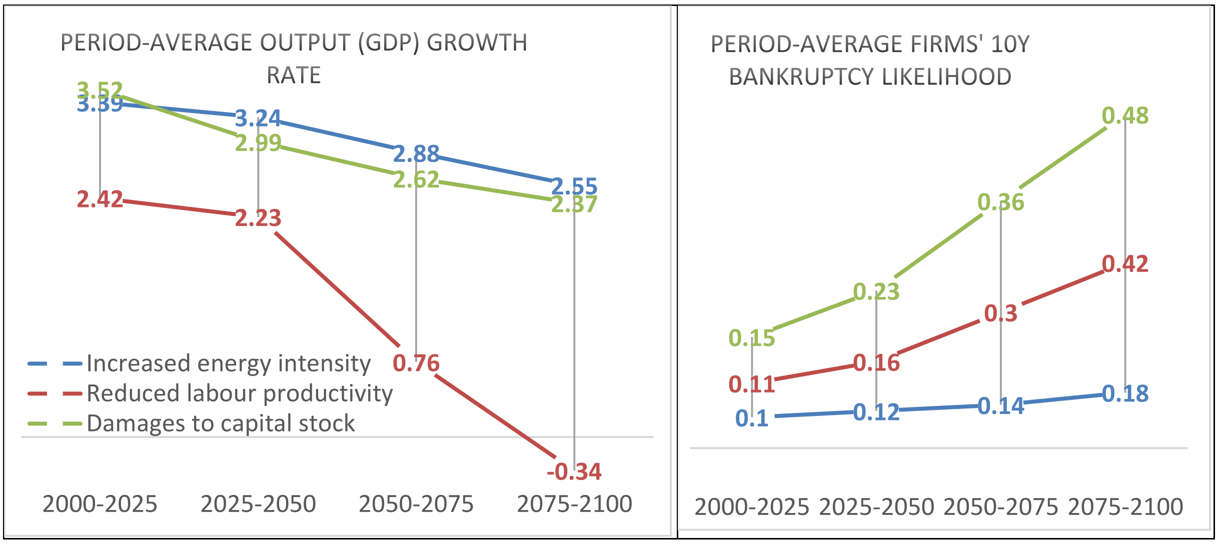


Figure 19: Left - average growth rates of the EU economy (a proxy for economic impacts); Right - average firms' 10-years likelihood of bankruptcy (a proxy for financial sector impacts); in four quarters of the simulation period (2000-2100) in the reference scenario (consistent with RCP8.5, +2.8 to 5.5°C), for three types of climate damage: higher energy intensity; lower labour productivity and damage to capital stocks.

A growing body of literature argues that future climate impacts should not be seen just as threats, but also as opportunities to foster certain trajectories of technological and societal development. Europe can move towards a sustainable and innovation-friendly growth-path if it implements the right policy mix to sustain a green transition, with economic growth decoupled from greenhouse gas emissions (see sections 2.3 and 2.4).

2.3. Visions of sustainable development

IMPRESSIONS worked with experts and stakeholders to discuss deeply held views about what they want the world to look like in the year 2100. Through this process, five aspirational visions were developed - one for each IMPRESSIONS case study. The visions are not restricted to our response to climate change, but consider broader global issues. Each vision differs to some extent as it reflects locally-specific issues and perspectives. However, some aspirations are common across all visions, such as a call for equity among citizens and societies; sustainable agriculture, water and energy systems; and transparent, accountable, democratic and participatory governance.

Through a stakeholder dialogue across the European case studies, major elements of the European, Hungarian, Scottish and Iberian visions were consolidated towards a common vision for Europe in 2100 (Figure 20). The common vision (and the case study-specific visions) can be used by decision-makers to set long-term goals and develop strategies to achieve and measure these goals. The visions are also an essential step in the process of creating pathways and strategies for adaptation, mitigation and transformation in the face of climate change.

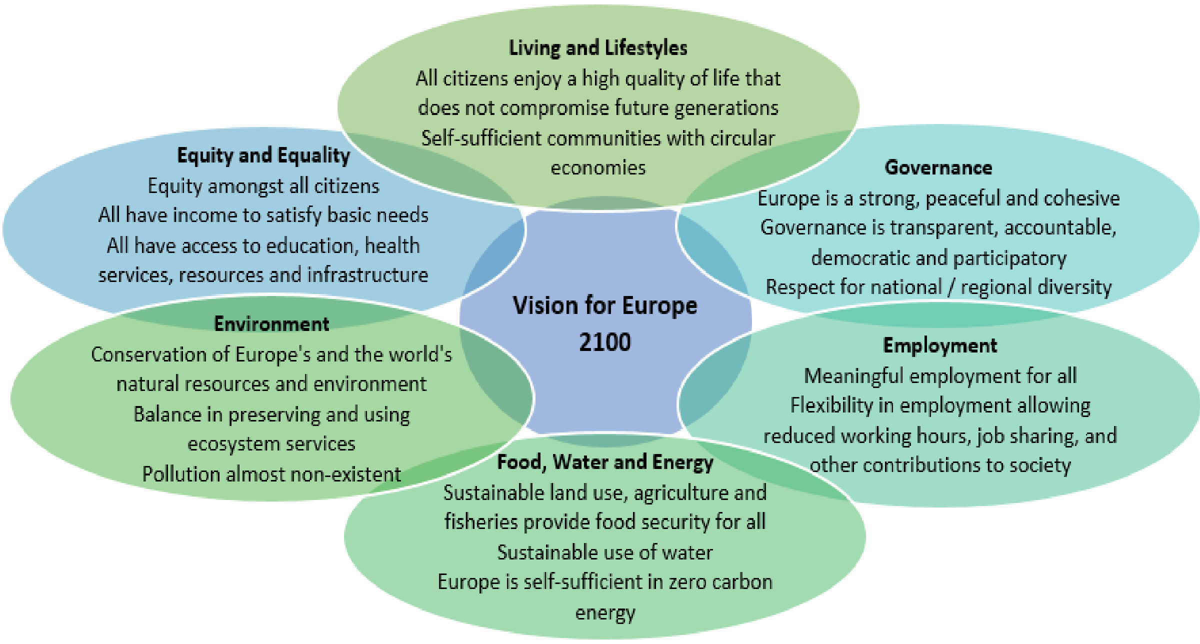


Figure 20: Elements of a common vision for sustainable development in Europe in 2100 developed with stakeholders from four of the IMPRESSIONS case studies.

2.4. Adaptation, mitigation and transformation pathways

Transformative approaches are needed to meet the Paris Agreement's goal of keeping global mean temperatures below 2°C (and ideally below 1.5°C) above pre-industrial levels, as well as to adapt to and cope with severe climate change impacts. IMPRESSIONS has co-created a suite of transformative mitigation and adaptation pathways to avoid the most dangerous impacts of climate change, build the capacities to respond to climate impacts and create opportunities to deliver multiple benefits.

A pathway approach starts from a long-term vision for sustainability and resilience ('Where do we want to be in the future?') and 'backcasts' possible courses of action ('How do we get to the future we want?'). Each pathway addresses one or more of the vision elements, which could relate to areas such as lifestyles, equality, governance and environmental protection. Pathways are composed of one or more alternative or complementary strategies, with each strategy consisting of short-, medium- and long-term actions that are assigned to different actors. Short-term and medium-term actions can remove obstacles and pave the way for long-term actions that are more daring and radical.

IMPRESSIONS stakeholders and researchers co-created a suite of pathways to support society in moving towards their vision (section 2.3) under the socio-economic constraints within each combined scenario (section 2.1). The aim was to identify additional strategies that are needed to reach the vision on top of the level of adaptation/mitigation already present in the input scenario. The scenarios provide different risks, constraints and opportunities. For example, actions in the SSP3 scenario, which features intense geopolitical conflict, are predominantly 'bottom-up', driven by local communities that self-organise to build self-sufficiency. In the SSP4 scenario, which features high inequality, the centralised authority of a strong elite enables a strategic top-down approach to planning, and in the techno-centric SSP5 scenario many of the actions are market-based. An iterative co-creation process between IMPRESSIONS experts and stakeholders enabled pathways to be analysed and verified between the workshop cycles.

The pathways identified by stakeholders include strategies and actions for technological innovation (e.g. renewable energy, water efficiency), nature-based solutions (e.g. sustainable urban drainage systems, renaturing river banks), and strong regulations and incentives to encourage sustainable lifestyles, innovation and economic activities. Three groups of transformative mitigation and adaptation pathways were developed that are robust across the different case studies and scenarios. Together, these pathways contribute towards achieving a long-term vision for a sustainable and resilient Europe at multiple scales. They are:

- **Shift towards sustainable lifestyles:** a cultural change in ways of living, commuting, producing, purchasing and learning for a reflexive and sustainability-oriented society. Strategies include establishing holistic and equitable education and health systems, supporting local communities and markets, and encouraging sustainable production and consumption through regulation and raising awareness. Transformative solutions include local currencies, environmental tax reform and a Sustainable Economy Fund.
- **Establish good governance systems for sustainability:** putting in place the conditions for participatory, transparent, learning-based and multi-level governance in Europe. Strategies include strengthening collaboration for sustainability through international and transboundary alliances; and decentralising decision-making within multi-level structures to pay attention to local opportunities and needs. Transformative solutions include participatory democracy and establishing a small "labs" approach to governance.
- **Promote integrated and sustainable resource management:** shifting towards context-sensitive, multi-functional and efficient resource management for environmental protection, resource security and European self-sufficiency. Strategies address water, energy, food, land-use and biodiversity holistically, to create synergies and alleviate trade-offs. Transformative solutions include the densification and energy self-sufficiency of cities, and a reform of the Common Agriculture Policy (CAP) with a greater focus on the bio-economy and community-based agriculture.

More specific strategies and pathways are summarised below for the different policy sectors:

- **Agriculture:** Sustainable low-input agriculture (including organic farming) offers a transformative pathway with benefits for both climate adaptation and mitigation. However, if yields per hectare are lower then the area needed for farming could expand (at the expense of forests), with negative impacts for climate and possibly biodiversity. This can be partly offset by a shift to more plant-based diets.
- **Forestry:** Forest managers can adapt to climate change by switching to better-adapted species and by planting a mix of diverse species in each stand to improve resilience. However, biodiversity and landscape impacts should be considered if native species are replaced with non-native species. Integrated land use planning should be used to optimise forest area, in view of the essential role that European forests and forest products play in achieving climate mitigation targets through storing and sequestering carbon, in addition to providing multiple additional benefits to society.
- **Biodiversity:** Urgent targeted interventions are needed to avoid a serious loss of biodiversity, including extending networks of protected areas and habitats across Europe to enable species to migrate in response to climate change, but these will not be enough. Co-ordinated action at the landscape scale is the key, bringing together the agriculture, forestry, water, urban development and biodiversity sectors to exploit synergies and minimise trade-offs. Integrated strategies such as promoting the use of nature-based solutions can provide multiple benefits for biodiversity, climate adaptation and mitigation.
- **Water:** Participatory integrated water and land management that considers the synergies and trade-offs between agriculture, forestry, water, energy and biodiversity can help to identify

and implement the most cost-effective and sustainable solutions, including nature-based solutions. Urgent investment is needed to reduce water demand and improve water use efficiency in regions vulnerable to water shortages.

- **Urban and health:** There is an urgent need to invest in climate-smart adaptation strategies based on energy-efficient buildings, passive cooling and nature-based solutions. Urban areas need to develop heat-wave plans, including protection for vulnerable citizens. Improved urban planning and housing design, including retro-fitting, can reduce heat-related impacts. There is a risk of maladaptation as increased use of energy-intensive space-cooling and heating, in response to increased weather extremes, will elevate greenhouse emissions.
- **Economy and finance:** There is a need for a rapid increase in carbon taxes both in Europe and worldwide (or, where this is not politically feasible, much stronger regulations and standards on energy use and efficiency), together with more government investment and public funding for low carbon technology. These interventions can reduce emissions at the same time as fostering growth and innovation.

Overall the key findings from the pathways analysis are:

- **Policy integration is crucial** to achieve the Paris Agreement goal and adapt to the impacts of climate and socio-economic change. An integrated perspective that takes into account the links between multiple policy domains, sectors and scales can facilitate synergies and alleviate trade-offs between adaptation, mitigation and other goals.
- **Pathways provide an organising framework and an effective approach for developing integrated courses of action** that deliver transformative change towards a long-term vision of sustainability and resilience. Positioning climate mitigation and adaptation within a long-term vision draws attention to the social, institutional, economic and technological actions that are required to achieve the 2^{o}C goal.
- **From the development of pathways, we conclude that institutions, behaviours and values need to change** in order to achieve long-term sustainability and resilience. Social cohesion, equitable access to services and increased knowledge and awareness can support individuals and communities to invest in sustainable technologies and adapt to climate change. Consistent, sustainability-oriented regulatory frameworks on sustainable production, consumption and resource management underpin the deep changes of values, lifestyles, markets and management approaches that are needed.
- **Europe can provide leadership** in motivating and coordinating global, national and regional action on climate, sustainability and resilience. Europe can lead by example, with transformative policies such as the CAP agri-environment schemes and (a revised) Energy Strategy, and strengthen international alliances to propel global sustainability commitments. Decisions should be taken in a highly participatory, transparent and reflexive manner that acknowledges that uncertainty cannot be controlled.
- **Innovations in technologies, infrastructure and land use** can help to provide multi-functional solutions to reduce emissions, adapt to climate change and enhance wellbeing. This includes both high-tech and low-tech solutions such as water-sensitive infrastructure, European smart grids and household rainwater harvesting, as well as social innovation and empowering local communities. Nature-based solutions provide cost-efficient co-benefits for the environment and people (e.g. biodiversity corridors, river re-naturalisation, green infrastructure).

2.5. Cross-border implications of high-end climate change: Interactions between Europe and Central Asia

In addition to assessing the impacts of climatic and socio-economic change in Europe, the IMPRESSIONS project looked at the question of cross-border impacts. Europe is connected to almost all parts of the globe, in one way or another. What would be the consequences for Europe of climatic and socio-economic changes taking place in other regions, given this global connectivity? This was considered in the Central Asia case study, which focused on the five post-Soviet Central Asian republics of Kazakhstan, Turkmenistan, Uzbekistan, Tajikistan and Kyrgyzstan that lie in a highly strategic position in the heart of Eurasia. Future developments here will have profound implications for the wider region, including Russia, China and the European Union.

A set of scenarios describing changes in Europe and Central Asia were co-developed with stakeholders, to re-think EU strategy in this strategically important region. By 2100, average temperature increase in Central Asia will be 50% higher than the global average: +5.1°C under RCP8.5. The frequency and magnitude of extreme weather events (heat, precipitation and droughts) will also increase. Impacts on water are critical. Glaciers are already shrinking but may reduce by 60% or more by the end of the century, increasing peak river flows. Flows in the two main catchments - Amu Darya and Syr Darya – are predicted to increase by 5-8% this century and up to 20-30% in springtime.

Changes to run-off in the “water tower” of Central Asia will cascade down into other sectors and systems. The risks depend critically on the extent to which agreement can be reached to build dams, regulate flows and optimise trade-offs between energy production (in winter) and irrigation (in summer). These dynamics are poorly modelled, but impacts on food security and agricultural exports could be severe. Cotton production could decrease between 11% and 23% by 2050; wheat production might experience significant losses or even productivity gains of up to 10% if irrigated and optimally managed. Limiting climate change to below 2°C also poses risks to oil and gas exporting regimes like Kazakhstan, Turkmenistan and Uzbekistan. Leaving Central Asian fossil fuels in the ground, which would be necessary to meet the goals of the Paris Agreement, would change the EU’s interests in Central Asia, which are currently influenced heavily by energy.

External players like the EU, as well as influential powers such as Russia and China, may wish to see the Central Asia region develop in different ways, depending on their strategic interests and based on their own “competitive advantages” to engage in the region. When developing strategies to bring about transformative change for sustainability, power and political strategy cannot be ignored. The EU’s competitive advantages in Central Asia include high capacities and credibility on education, environment, private sector, trade, rural development and health, all of which were deemed of high relevance to the sustainable future of Central Asia by stakeholders. In seeking to complement the role of other potentially like-minded external actors in Central Asia, the EU is viewed as particularly strong in regulatory design – principally for private sector governance, trade facilitation, quality control, training and research and development. These strengths could help to address two potentially transformative solutions to Central Asian challenges:

- **Transboundary water governance:** Reaching agreement on how to manage transboundary water would create positive ripple effects for adaptation across borders and sectors in Central Asia, from energy to food to health and regional trade, however unlikely that prospect currently appears.
- **Regional connectivity:** Ambitious attempts to revive the Silk Roads of old, by connecting Central Asia internally and to its neighbours, could boost stability and development. Sustainable versions of China’s Belt and Road Initiative therefore hold potential to transform Central Asia in ways that support climate resilient societal transformations.

The EU will have to adapt to climate changes beyond its borders as well as at home. However, the EU's current Central Asia Strategy is not robust to a range of different plausible futures in the region; it does not take proper account of the way in which external actors might respond to changes in Central Asia, particularly under conditions of extreme climate change. Cross-sectoral and transboundary climate change impacts could destabilise the region because of its delicate resource interdependencies and growing tensions. However, climate change also offers a seemingly unlikely but positive opportunity to build regional resilience. Achieving a new regional transboundary water-sharing agreement would be a positive "tipping point", unlocking huge potential for adaptation and mitigation. Also, external interest in connecting Central Asia to markets in China and Europe could boost adaptive capacity in Central Asia.

3. Potential impact

3.1. Socio-economic impact and wider societal implications

3.1.1. What are the key impacts?

IMPRESSIONS has addressed the major societal challenge of coping with climate change by identifying sustainable, cost-effective strategies where synergies between adaptation and mitigation can be realised and conflicts minimised. Results have been produced in partnership with, and therefore supported by, a wide range of decision-makers across Europe. This stakeholder-led approach ensured that the research was driven by the priorities of decision-makers from key economic and social sectors so that significant co-learning could be achieved. The use of case studies also ensured that project results are rooted in real-world policy-making. Overall, this approach has enabled decision-makers in the IMPRESSIONS case studies to identify robust, innovative and effective solutions for addressing high-end climate change. It highlighted the societal and policy innovations and transformations needed to realise synergies between adaptation and mitigation and achieve a sustainable green economy.

Specifically, IMPRESSIONS has enhanced our understanding of the impacts of high-end climate change combined with socio-economic change on a number of policy sectors and identified possible responses in a number of ways:

Firstly, the multi-scale and cross-sectoral integrated modelling has provided an improved quantification of the impacts and vulnerability of major social and economic sectors, especially in the case study regions. This, through the stakeholder workshops and our dissemination activities, has already enabled stakeholders, including those involved in policy and decision-making, to have a better understanding of, and evidence base on, the potential challenges of high-end climate change. Thus enabling them to make more informed decisions.

Secondly, the IMPRESSIONS modelling has facilitated the assessment of the existing adaptive capacity of European society and has explored whether actions within harmonised adaptation and mitigation pathways are likely to develop sufficient adaptive capacity to enable successful adaptation to future impacts of high-end climate change scenarios. It has shown that, in many cases, there are societal challenges to coping with these projected high-end scenarios, and highlighted the geographical, sectoral and capacity differences across Europe. This information is important for identifying specific societal vulnerabilities and for developing appropriate responses for future proofing society.

Thirdly, the visioning and pathways research in the IMPRESSIONS case studies have shown both the extent to which aspirational visions might be achieved and the pathways for reaching the different elements of them. The critical advance made in IMPRESSIONS compared to previous research on transitional pathways is that interactions between different elements of the pathways are taken into consideration, leading to the development of integrated pathways. These are important in demonstrating how society needs to respond across a range of socio-economic areas and at different points in time, in order to avoid trade-offs in actions, as well as identifying potential synergies which would lead to (cost)effective responses. In each case study, the set of sustainable development transition pathways offer options for harmonising adaptation and mitigation strategies to enable society to adapt effectively to potential impacts under high-end scenarios and across multiple scales.

An important outcome of the comparison of the transformative mitigation and adaptation pathways across the case studies was the identification of three common robust pathways, which were also applicable across the scenarios (see Section 2.4). These provide a clear indication of possible societal strategies for mitigating and adapting to climate change, which could be used by decision-makers to inform actions, capacity building and policy for preparing for future socio-economic challenges driven by climate change. Based on the analysis of the pathways across case studies, IMPRESSIONS developed the following policy recommendations:

- **Develop integrated climate mitigation and adaptation policies to achieve long-term sustainability and resilience goals.** An integrated perspective focuses attention on changing the underlying social, institutional, economic and technological conditions that produce high emissions, vulnerability and inequality. The pathways show many possible synergies between climate change mitigation, adaptation, and social and environmental wellbeing, such as through strengthening local, low-carbon and self-sufficient communities. They also reveal trade-offs, such as between increased use of air conditioning and carbon emissions.

- **Invest in social and human capital to support shifts to sustainable lifestyles.** The pathways underscore the opportunities arising from strong social cohesion at European, national, regional and local levels, for achieving a united Europe in the face of climate change and other risks and for enabling community-based adaptation. Social cohesion requires investments in new education systems that internalise environmental and social values and knowledge (e.g. respect for the environment and people), strengthening local communities and diversified local markets, and setting up social protection and solidarity mechanisms.

- **Strengthen participatory, transparent and learning-based governance at multiple levels.** Democratic, flexible and cooperative governance systems are better able to deal with the multiple challenges that today's societies face. Multi-level and democratic decision-making fosters a common European identity and taps into the skills of diverse societal actors. It promotes cooperation across scales to take local priorities, needs and opportunities into account for a Europe that is sustainable and resilient as a whole. Governance experimentation is an important mechanism to deal with deep uncertainty and complex problems that have no 'silver bullet' solution.

- **Put in place strong and consistent regulatory frameworks and policies to ensure sustainable resource management, production and consumption.** Stringent, sustainability-oriented regulatory frameworks on sustainable resource management, production and consumption underpin the deep behavioural and institutional changes of values, lifestyles, markets and management approaches that are needed to meet climate and social goals. The frameworks need to be translated into consistent sets of policies, including regulation, taxes and incentives (e.g. carbon tax, green energy subsidies).

- **Innovate 'hard' and 'soft' measures for sustainable water, energy and agriculture.** Profound innovations in technologies, infrastructure and land-use are needed to shift towards low-carbon, sustainable and resilient societies. This encompasses innovative high-tech (e.g. smart grids, water desalination) as well as low-tech solutions (e.g. household rainwater harvesting). Nature-based solutions should be strengthened as a way to provide cost-efficient co-benefits for adaptation, mitigation, the environment and people (e.g. biodiversity corridors, natural flood management, river re-naturalisation, green infrastructure).

Similar sets of policy recommendations were co-created for each policy sector and each case study to provide examples of context specific actions. If these are implemented, then society will become better adapted to climate change, as well as contribute to climate mitigation leading to greater climate resilience and a more sustainable future. Some examples are given below:

- **Cross-sectoral:** Apply a systems-based perspective in policy development that involves integrated solutions to address water management, land use planning and biodiversity conservation together (e.g. conservation agriculture; catchment management; ecosystem-based adaptation), to exploit synergies and reduce trade-offs between these sectors. This includes promoting solutions with benefits for both climate adaptation and mitigation.

- **Agriculture:** Reform the CAP to direct a higher proportion of the funding towards supporting sustainable climate-smart agriculture, biodiversity enhancements and water efficiency, with more local and more transparent delivery and monitoring mechanisms, such as via 'water funds'. Broaden the CAP to include other land managers. Support change in consumer patterns towards organic, low-meat or more locally produced products; this can support local job creation, reduce greenhouse gas emissions, air and water pollution and increase the amount of land available for wildlife habitat. Support farmers to adapt to changing conditions through training and financial support to enable them to adopt novel land uses and management methods, e.g. agroforestry, conservation agriculture or new crop varieties. Support rural agricultural employment in southern Europe as profitability declines due to water scarcity. Diversify crop production to build resilience in the face of uncertain climate impacts, and encourage urban agriculture.

- **Forestry:** Consider switching to more climatically suitable tree species to adapt to future climate change, but plan the timing of the switch carefully, and consider the implications for native biodiversity and characteristic landscapes. Shift to more diverse stands to improve resilience to future change, including pests and diseases. Integrated land use planning should consider trade-offs between forests, agriculture and other land uses in the light of the essential role of forests in climate mitigation.

- **Biodiversity:** Adapt the existing network of protected areas to cope with climate change, using species dispersal models as a guide, and new areas in more suitable climate zones may need to be created. Strengthen the connecting network of habitats outside protected areas to enable species to migrate to suitable new habitats to cope with climate and land use change. Protect/create green corridors through urban and intensive agricultural areas. Clear planning guidelines and incentives are needed to encourage greater use of nature-based solutions and green infrastructure in both urban and rural areas, as they can provide benefits for biodiversity, climate adaptation and mitigation and other goals.

- **Water:** Avoid building new development in areas vulnerable to flooding and consider the need to move the most vulnerable communities to safer areas. Make more use of innovative and cost-effective nature-based solutions and grey-green infrastructure for flood protection, water quality and natural cooling of water. Prioritise investments to increase water use efficiency (and wider resource efficiency to minimise the consumption of 'embedded water') in line with the "Blueprint to safeguard Europe's water". Explore innovative options for distributed (non-reservoir) water storage, e.g. groundwater recharge; storage in soils; small lakes on farms. Abstraction taxes should include all externalities, and abstraction licenses should be time-limited so they can adapt to the changing climate. Invest in technologies for re-use of treated wastewater and stormwater, in line with the Urban Wastewater Treatment Directive. Promote behaviour change to cut water demand in all sectors (household, agriculture, business and energy), using the education system, awareness campaigns, regulations and incentives.

- **Urban and health:** Plan for compact, green, climate-smart and sustainable cities. This would require strong planning regulations to achieve the targeted residential densities of city areas, while protecting and enhancing the green and blue spaces that are needed for climate adaptation, health and wellbeing. Develop climate-smart adaptation plans that maximise synergies with climate mitigation, for example, buildings with passive cooling and nature-based solutions (such as green space and permeable surfaces, green roofs and walls, street trees, parks and wetlands) that provide cooling, shading and stormwater infiltration or retention together with other health and wellbeing benefits. To mitigate the impacts of any increase in the use of air conditioning, a rapid shift towards zero-carbon/renewable electricity should be promoted.

- **Economy and finance:** Increase government investment and public funding to support the development and uptake of low carbon energy generation, energy storage systems and other sustainable technologies. Increase carbon taxes in Europe, and encourage wider mitigation efforts globally through international coordination. Where this is not politically feasible, implement much stronger regulations and standards for energy efficiency and low-carbon energy. Foster both the resilience of financial institutions to extraordinary losses and their willingness to invest in green and climate management technologies. Europe might be inspired by the role covered by public banks around the world and, especially, in China.

IMPRESSIONS research has shown that all impacts are more severe under higher levels of climate change and adaptation pathways cannot avoid all impacts, so both mitigation and adaptation are essential. Strengthening commitments to meet the Paris Agreement in conjunction with pursuing the UN Agenda 2030 Sustainable Development Goals is therefore critical. Early moves towards sustainability, as shown in the IMPRESSIONS modelling results for the SSP1 scenarios, make it possible to avoid some of the worst impacts. The IMPRESSIONS pathways therefore provide a strong evidence base that governments, civil society and businesses can utilise to help make Europe more financially and societally secure under high-end climate change.

3.1.2. Who has been impacted?

Our various dissemination activities (see Section 3.2) demonstrate that a number of different groups in society have been reached by IMPRESSIONS research and outputs. The most direct influence and intensive interaction has been with our stakeholders, with whom the project has been co-designed and implemented. The engagement with case study stakeholders has built capacity and a deeper understanding of the wide implications of climate change for society, so that they can use the new information and train others to sustain a lasting legacy of impacts beyond the lifetime of the project.

A survey was sent to all 195 stakeholders that have been engaged in various ways in the IMPRESSIONS project, of whom 42 responded, covering all five case studies. It showed that 88% of the respondents either agree or strongly agree that they have learned new insights through the project. The most important insights that they gained were: high-end climate change is a very probable scenario; such scenarios are likely to be difficult to cope with in comparison to ≤ 2°C scenarios; and such scenarios result in significant impacts for their case study area and for the sector where the stakeholder works. Almost half (44%) of the stakeholder responses highlighted the IMPRESSIONS workshops as particularly important sources of knowledge on high-end climate change. In addition, they emphasised talking to researchers and reading project reports and policy briefs as important knowledge sources. Approximately two thirds of the respondents agreed or strongly agreed that they have changed their mind about the relevance of high-end climate change through their involvement in the project. The stakeholders had changed their mind about high-end climate change representing many additional difficulties for adaptation and that it represents a reality for which they are frequently not prepared, or had not anticipated. Over half of the respondents stated that they had changed their own decision-making process to some extent as a result of being involved in the project. How they are now incorporating high-end climate change into their work varied (Figure 21), but most were including/going to include high-end climate change as part of their overall decision-making about climate change.

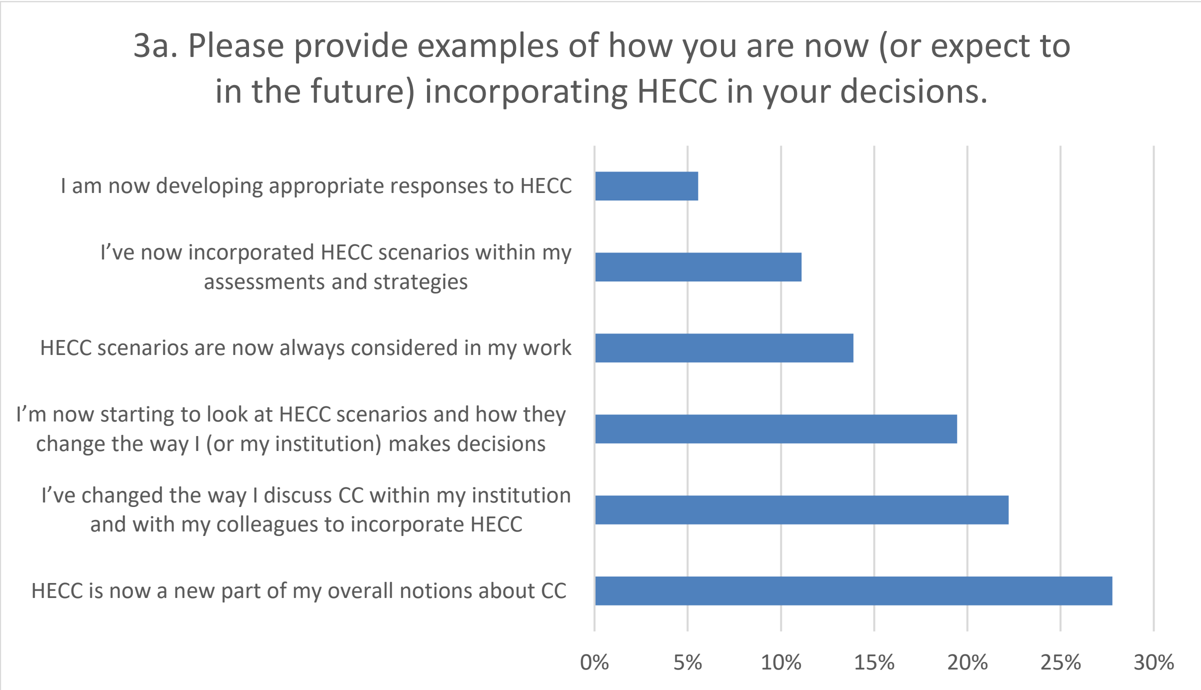


Figure 21: Stakeholder responses to a survey question on how involvement in the IMPRESSIONS project has affected how they are incorporating high-end climate change (HECC) in their decisions (n=42).

The project has not only had an impact on the case study stakeholders, but also through the IMPRESSIONS Summer School (see Section 3.2), where we have been able to demonstrate to both young researchers and decision-makers from across the globe, the importance of an integrated approach to addressing high-end climate change. Several were keen to apply the IMPRESSIONS approach or elements of it in their own work, with the practitioners/policy-makers being particularly interested in applying the visioning and pathway development. For example, one researcher who participated in the Summer School said "I would like to use this methodology in my own research, so it was very nice to be able to practice with it", whilst a practitioner commented "I will definitely use it for our climate change action plan development projects for the two cities". Thus, the IMPRESSIONS approach is being applied beyond the project leading to wider future impacts for society across Europe and the globe.

3.2. Dissemination activities and exploitation of results

During the whole lifetime of IMPRESSIONS information related to the project and its outcomes were widely popularised using a full range of communication and dissemination approaches.

- IMPRESSIONS logo ( ) – designing the IMPRESSIONS logo was one of the first steps taken. It introduced the project and helped the external audience to easily identify it.

- Website including an internal communication platform (http://impressions-project.eu/) – the IMPRESSIONS website was launched at the very beginning of the project. It was designed in a way to make it attractive to the different target groups, user-friendly, interactive and kept up to date with information. The website has two distinct areas: (i) public website area containing general information about the project and its development, and links to project outputs, which is accessible to anyone; and (ii) private (password protected) website area called the Internal Communication Platform (ICP) which supported the smooth workflow between project partners. To broaden the impact of IMPRESSIONS and to promote its results to users of social networks, profiles of IMPRESSIONS were created in Twitter (362 followers at the end of the project), Facebook (97 likes received during the project lifetime), LinkedIn (37 members), YouTube and Google+.

  From the creation of the website to the end of the project the IMPRESSIONS website was visited by 39,776 users with a total of 63,486 sessions and 193,671 page views. The average page depth of the website is 3.05 pages per session. The geographic distribution of IMPRESSIONS website visits shows that the project has engaged audiences across the world (Figure 22). The IMPRESSIONS website has been visited by people from nearly 200 countries, most visits coming from United States, United Kingdom, Germany India and Italy, followed by Spain, France, Netherlands, Brazil and Belgium.

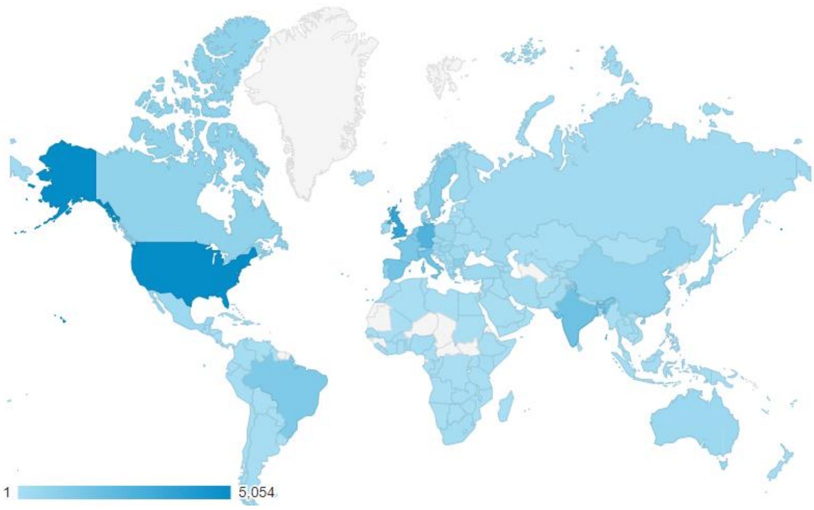


Figure 22: Map of the geographic distribution of IMPRESSIONS website audiences. Shading indicates number of website visits.

The IMPRESSIONS website will be maintained and kept alive for a further 5 years after the project's end. The large amounts IMPRESSIONS climate data are stored in a secure environment to ensure perennity and, in the spirit of research integrity, future re-use both by IMPRESSIONS scientists and outside initiatives or projects who might utilise it in future research.

- A common webpage (http://highendclimateresearch.eu/) for the three EU FP7 "sister" projects (IMPRESSIONS, HELIX and RISES-AM) funded under the same call on high-end climate change impacts and adaptation has been created.

- IMPRESSIONS outreach materials – used to announce the project and provide relevant information to the diverse stakeholders, disseminated in both electronic and printed form. IMPRESSIONS produced: an introductory flyer (available in 11 European languages), IMPRESSIONS postcard; IMPRESSIONS poster; IMPRESSIONS overview poster; case study posters; infographics, visions posters and pathways murals, eight issues of the IMPRESSIONS newsletter, five press releases, thirteen policy briefs, over twenty dissemination videos, and numerous other outreach materials to promote and support specific events or project outcomes, and a policy booklet (see below).

- Policy booklet "High-end Climate Change in Europe: Impacts, Vulnerability and Adaptation" – the booklet is the result of the joint effort of over 150 researchers from leading scientific institutions across Europe, working on IMPRESSIONS and two other major EU-funded projects HELIX and RISES-AM, sister projects of IMPRESSIONS. Key results from the three projects regarding sectors, such as food and water security, biodiversity, human health, coasts and human migration can be freely accessed in the joint policy booklet. The booklet was distributed through personal and institutional networks and is freely available on the IMPRESSIONS website (Figure 23).

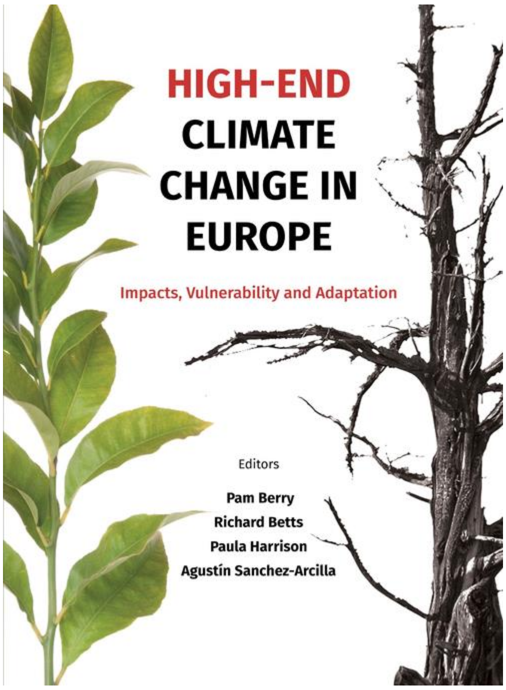


Figure 23: IMPRESSIONS policy booklet cover.

- IMPRESSIONS newsletter - a news bulletin in electronic format, containing and highlighting news of interest for the IMPRESSIONS stakeholders was issued periodically.

- Press releases – a total of five press releases marking important steps in the project implementation were prepared and published via EurekAlert, one of world leading distributors of science news. The most recent press release "High-end solutions to extreme climate change in a new online resource" advertised the High-end Solutions Information Hub as an IMPRESSIONS major output.

- Policy briefs – the IMPRESSIONS research has been synthesized into 13 policy briefs by case study, by sector and by theme to provide policy recommendations based on project results, designed for a wide range of stakeholders, including policy- and decision-makers.

- IMPRESSIONS videos – created as an alternative and easy way for stakeholders and the general public to learn more about the project. The **Inside IMPRESSIONS** series gives an overview of the project, its aims and objectives, and the work progress made. Project outcomes, stakeholder engagement and other useful information from events organised by IMPRESSIONS can be found in the **IMPRESSIONS stakeholder workshops video reports**.

- IMPRESSIONS final video collection – is a series of 12 linked videos produced and released to raise awareness about the methodology and final outcomes of IMPRESSIONS. They support practitioners and policy-makers in gaining quick and focused insights on how to choose and manage innovative solutions for tackling high-end climate change. All videos were made available on YouTube thus giving people the opportunity to share any of the videos on their website, blog and/or social media account so the IMPRESSIONS message can be spread widely.

- The Bond You Hold – is an innovative theatre performance illustrating the dynamic relation between climate and humans in a world beyond 2°C warming, created through an exciting collaboration between IMPRESSIONS scientists and artists from the Stockholm Resilience Centre. In addition, a number of other performances and art installations were created and used to raise awareness of high-end climate change within the Iberian stakeholder workshops.

- Media presence - IMPRESSIONS appeared in a variety of interviews and broadcasts on TV and radio, as well as in regional and national print and web publications across Europe.

- High-end solutions Information Hub – the High-end Solutions Information Hub is a synthesis of the knowledge and results from IMPRESSIONS acquired during the 5-year collaboration of 26 partners from different scientific backgrounds and 16 European countries, who have worked intensively with numerous stakeholders. This is one of the major products produced by the project to ensure uptake of the projects outcomes. It provides comprehensive knowledge on the nature and scale of more extreme and long-term consequences of climate and socio-economic change. With strong visual illustration of the researched topics, the tool is created to guide scientists and decision-makers working on adaptation, mitigation and sustainable development through the collections of results, recommendations and methods. The platform will be maintained after the project lifetime to ensure the project outputs are widely available over the longer-term.

- IMPRESSIONS work has been published in 74 peer-reviewed journal articles and 15 book chapters, covering leading peer-reviewed journals, amongst them: Nature Climate Change, Regional Environmental Change, Science of the Total Environment, Ecological Economics, Environmental Science and Policy, Landscape Ecology, Society & Natural Resources, etc. These are complemented by six PhD thesis completed.

- An IMPRESSIONS Special Issue featuring 15 papers detailing key project methods, results and conclusions was published in the journal Regional Environmental Change.

- Training and sharing of skills – an IMPRESSIONS Summer School was organised to introduce IMPRESSIONS methods and tools, and demonstrate their application for studying the impacts of climate and socio-economic change in Bulgaria. The young scientists and practitioners got together for a five-day summer school in Sofia, Bulgaria and explored the different ways to mitigate and adapt to high-end climate change scenarios.

- Communication and dissemination activities – IMPRESSIONS partners' participated in or organised over 350 international and national conferences, workshops, meetings and other events related to potential solutions to the impacts and risks associated with high-end climate change. Between 2015 and 2018, IMPRESSIONS organised 15 **IMPRESSIONS stakeholder workshops,** three workshops per case study (Hungary, Scotland, Iberia, Europe and Central Asia) to facilitate the co-design and co-creation of the project methodology and results. The workshops were professionally facilitated and resulted in stakeholder-led scenarios, visions adaptation and mitigation pathways, and integrated and transformative solutions to high-end climate change. In July 2015, IMPRESSIONS was at **"Our Common Futures under Climate Change"**, which was the largest forum for the scientific community to come together ahead of the COP21 of the UNFCCC in 2015. IMPRESSIONS co-organised a session entitled "A world above 2^{o}C global warming: understanding risks and developing transformative solutions" which was attended by more than 70 people. IMPRESSIONS also participated in the **UNFCCC COP21**, held in December 2015 in Paris, France, where the project took part in the Rio Conventions Pavilion (side event organised by the Secretariats of the Rio Conventions and the Global Environment Facility) session focused on synergies and trade-offs in land-based climate mitigation and biodiversity. IMPRESSIONS, alongside its sister-projects HELIX and RISES-AM, also shared insights during a side-event at **COP23** held in Bonn, Germany, in November 2017. Looking at different aspects of high-end climate change, the three projects presented results on impacts and the potential for adaptation in a number of sectors and at a range of scales from global to individual cities, including coastal areas. Another important event, organised by IMPRESSIONS, HELIX and RISES-AM projects, was the **European Climate Change Adaptation conference (ECCA 2017): Our Climate Ready Future**, held in the City of Glasgow in June 2017. Over 850 participants from business, industry, NGOs, local government and communities were brought together to share knowledge, ideas and experience with leading researchers and policy-makers. The event inspired people to work together to discover and deliver positive climate adaptation solutions that can strengthen society, revitalise local economies and enhance the environment. IMPRESSIONS was also involved in the ECCA 2015 conference, held in Copenhagen, and is supporting the organisation of ECCA 2019, to be held in Lisbon in May 2019. IMPRESSIONS was also at the **Adaptation Futures 2016 Conference,** held in Rotterdam in May 2016, and the **Adaptation Futures 2018 Conference**, held in June 2018 in Cape Town, South Africa. The 2018 conference aimed to facilitate dialogues for solutions between key actors from diverse perspectives and regions and attracted over 1300 scientists, practitioners, business leaders and policy-makers from around the world. During the event, IMPRESSIONS partners held several sessions presenting important scientific results. IMPRESSIONS also had a stand at the event allowing the dissemination of key project results, including the demonstrating and collecting feedback about online resources. IMPRESSIONS has also had key involvement in many other conferences, examples for 2018 include: the 5th European Congress of Conservation Biology, the European Ecosystem Service Partnership Conference, the 5th Nordic Conference on Climate Change Adaptation, the International Association of Hydrogeologists conference, the European Association for Evolutionary Political Economy conference, the International Sustainability Transitions (IST) conference, and the Society for Computational Economics 24th International Conference. Finally, the **IMPRESSIONS Policy Day**, the projects final dissemination event, was held in Brussels on 22 October 2018. The event presented IMPRESSIONS methods and results on scenarios, modelling, visions, pathways and solutions, and discussed finding with participants from the Commission Services through panel discussions and subsequent one-to-one meetings. Further information on the dissemination activities is available in the complete list of dissemination activities.

- Involvement in IPCC and IPBES - IMPRESSIONS research was strongly cited in the IPCC Special Report on 1.5^{o}C, particularly on pathways and transformative climate science for sustainable development. IMPRESSIONS partners are also involved in the IPCC Special Report on Climate Change and Land, as well as co-chairing the IPCC Task Group on Data and Scenario Support for Impact and Climate Analysis (TGICA). IMPRESSIONS partners have also been highly active in the Intergovernmental science-policy Platform on Biodiversity & Ecosystem Services (IPBES), particularly the regional assessment for Europe and Central Asia, which was published in 2018 and included work from IMPRESSIONS on scenarios, visions and pathways to sustainable futures.

4. Contacts for further information

For further information:

- Visit the project website: http://www.IMPRESSIONS-project.eu

- Contact the Project Coordinator: Professor Paula Harrison, UK Research & Innovation (UKRI) - Centre for Ecology & Hydrology, Lancaster Environment Centre, Bailrigg, Lancaster, LA1 4AP, United Kingdom; email: PaulaHarrison@ceh.ac.uk

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