



Modelling Climate Change Impacts, Adaptation and Vulnerability in Europe

Deliverable D3B.2

March 2017

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Prepared under contract from the European Commission

Contract n° 603416
 Collaborative project
 FP7 Environment

Project acronym: **IMPRESSIONS**
 Project full title: **Impacts and Risks from High-end Scenarios: Strategies for Innovative Solutions**
 Start of the project: 01 November 2013
 Duration: 60 months
 Project coordinator: NERC Centre for Ecology and Hydrology
 Project website: www.impressions-project.eu

Deliverable title: European scale CCIAM applications
 Deliverable n°: D3B.2
 Nature of the deliverable: Report
 Dissemination level: Public

WP responsible: WP3
 Lead beneficiary: CU

Citation: Holman et al. (2017). Modelling Climate Change Impacts, Adaptation and Vulnerability in Europe. IMPRESSIONS Deliverable D3B.2. Available from www.impressions-project.eu

Due date of deliverable: Month 40
 Actual submission date: Month 41

Deliverable status:

Version	Status	Date	Author(s)
1.1	Draft	15 February 2017	Ian Holman et al.
1.2	Draft	28 February 2017	Ian Holman et al.
1.3	Final	24 March 2017	Ian Holman et al.

The content of this deliverable does not necessarily reflect the official opinions of the European Commission or other institutions of the European Union.

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Preface

The European Commission-funded FP7 project IMPRESSIONS (Impacts and Risks from High-end Scenarios: Strategies for Innovative Solutions) is an ambitious study of the risks and consequences for Europe of a runaway greenhouse effect and the options available for averting its most adverse effects. Focusing on the high-end of projections of future climate change and operating in the context of alternative development pathways for Europe, the project seeks to simulate future impacts on natural resources, land use and societal well-being in Europe during the 21st century. It attempts this using a suite of single-sector and integrated multi-sector models that simulate the dynamics of climate change impacts and adaptive management using an iterative, time-dependent approach up to 2100. The options for adaptive management, including transformative change, are guided by stakeholder-led visions of a sustainable and equitable Europe by 2100.

This deliverable reports on the modelling of climate change impacts, adaptation and vulnerability (CCIAV) within Task 3B.4 for the European case study of IMPRESSIONS. The model improvements and development within the other three WP3B Tasks (Task 3B.1- further development of a regional integrated assessment model (rIAM) for Europe; Task 3B.2 - process-based impact modelling within Europe; and Task 3B.3 - the new agent-based model for Europe) were previously described in Deliverable 3B.1 (Holman et al., 2015). Many of the decisions taken that are reflected in this document were obtained at five IMPRESSIONS modelling workshops held in London (April 2014), Pisa (September/October 2014), Cranfield (March 2015), Copenhagen (December 2015) and Pisa (November 2016) as well as at General Assembly sessions in Oxford (January 2014), Barcelona (January 2015), Florence (January 2016) and Budapest (January 2017) and a combined WP2-3-4-5 workshop in Rotterdam (March 2017).

The application of the CCIAB models within the European case study links to other parts of the IMPRESSIONS project. Primarily this involves a relationship with the project scenario development (WP2) since the scenarios are key inputs to the models. There are also strong links to WP4 and 5 in terms of exploring future visions, and in defining pathways of adaptive actions including transformative solutions.

Summary

This deliverable describes the application of the climate change impact, adaptation and vulnerability (CCIAM) models within the European case study of IMPRESSIONS. The work was undertaken as part of WP3B which aimed to advance and apply European-scale methods and models to better quantify and understand impacts, risks, vulnerabilities and adaptation options associated with a range of scenarios for key economic, social and environmental sectors and their cross-sectoral interactions. Results from some of these analyses are reported here, while others planned for a later stage of the project will be reported in D3.2 (Comparison of modelling results across scales; due December 2017).

The climate scenarios selected for use in the IMPRESSIONS European case study cover a range of RCPs (2.6, 4.5 and 8.5) and GCM climate sensitivity (low, intermediate and high). As a result the European-average change in temperature for 2071-2100 relative to 1961-1990 ranges from 1.3 to 5.4°C; whilst annual precipitation change ranged from +1 to +13%. These were combined with the SSPs in an internally-consistent framework, so that RCP2.6 was combined with SSP1 and 4; RCP4.5 with SSP 1, 3 and 4 and RCP8.5 with SSP5.

A broad range of modelling outputs were developed within the European case study that cover different model types (agent-based models, physically-based models, meta-models), modelling approaches (scenario-neutral impact response surfaces vs scenario simulations) and system representation (sectoral models vs integrated modelling platforms). The modelling result show that high-end climate change will lead to significant impacts and vulnerabilities across Europe, but also strong spatial differences that provide opportunities in some regions. However, it is also clear that the differences due to future socio-economic change are as large, or even larger, than those directly due to climate change indicating the potential for European society to exert a strong positive or negative influence on Europe (and the rest of the world).

In collaboration with WP4 and 5, the European case study has evaluated the potential for adaptation, mitigation and transformative actions to move Europe towards a desired end-point in the face of the challenges of high-end climate change. This desired end-point (a Vision for Europe in 2100) was developed by stakeholders as part of the IMPRESSIONS participatory process. The stakeholders' Vision contains a diverse range of elements, some of which can be related to modelled indicators, but others which cannot. As a consequence, a twin-track approach was used to enable quantitative (model-based) and qualitative (expert-based) analyses of the effectiveness of the adaptation, mitigation and transformative actions within the stakeholders' pathways to achieve the desired Vision to be integrated. This analysis is ongoing and will feed into the forthcoming European Stakeholder Workshop in Troyes, France in May 2017.

1. Introduction

The objective for the European case study (WP3B) is to advance and apply European scale methods and models to better quantify and understand impacts, risks, vulnerabilities and adaptation options associated with a range of scenarios for key economic, social and environmental sectors and their cross-sectoral interactions. This deliverable describes the application of a range of climate change impact, adaptation and vulnerability (CCIAB) models within the European case study of IMPRESSIONS to address this objective.

The research is ongoing and, as such, this report offers a snapshot of the modelling activity within the IMPRESSIONS' European case study which will be further refined and iterated based on stakeholder feedback within the third set of Stakeholder workshops.

1.1. Description of Work

According to the Description of Work there is one main task contributing to D3B.2:

Task 3B.4: Application and comparison of the European CCIAB models

One of the main themes of the European case study is evaluating the effects of the WP2 climate and socio-economic conditions on European spatial land planning. The modelling will quantify the impacts of climate, exogenous (population migration, global food trade from WP3A) and endogenous (WP2 scenario quantification) socio-economic changes on the allocation of land, considering the competing pressures for food production, forestry, housing and biodiversity, and the cross-sectoral constraints of urban heat-related health, flood risk and water resource availability. The models from Tasks 3B.1 and 3B.2 will be used to investigate impact response surfaces which quantify risks for probabilistic projections (from WP2) and offer useful insights into possible non-linear responses or tipping points. Outputs will also be used to inform the WP4 backcasting exercise and to characterise the uncertainty in the time- and path-dependency of adaptation options, i.e. by modelling the likelihood of reaching the end-points of the transition management pathways. Comparisons will be undertaken for key sectors between the results of the cross-sectoral integrated assessment and process-based modelling to assess potential losses of information from different methodological approaches. Comparisons will also be made between the top-down modelling approaches from Tasks 3B.1 and 3B.2 with the bottom-up ABM approach from Task 3B.3 to analyse the additional information gained through using a complex systems approach to CCIAB assessment at the European scale.

This Deliverable reports most aspects of this task although some elements will be reported in more detail in the later Deliverable D3.2 (Comparison of modelling results across scales).

1.2. Case Study Ambition

The agreed aims for the European case study, which this deliverable supports, is:

“The ambition of the European case study is to develop new knowledge and evidence on the impacts of, and adaptation to, high-end scenarios (HES) on key ecosystem service indicators across Europe. Simulated changes in a range of urban, health, agricultural, forestry, water and biodiversity indicators over time under high-end climate and socio-economic scenarios will be used to help stakeholders and decision-makers develop long-term adaptation strategies for coping with HES.

The case study will consider how impacts and adaptation responses in one 'sector' can have positive or negative effects in other sectors. The representation of adaptation decision-making in computer models will be improved to better understand how the effectiveness of adaptation under HES is influenced by timing and by socio-economic constraints. The insights gained through the stakeholder-led activities will provide capacity building for key decision-makers with respect to adaptive learning for coping with high-end scenarios".

Within this case study ambition, it was agreed within the IMPRESSIONS project that the “decision-makers” represent the European Commission (and related institutions operating at the EU level) to make a clear distinction from the regional and national scale of the decision-makers within the Regional Case Studies. As such, key European policies related to our decision-makers are the Water Framework Directive (WFD), Common Agricultural Policy (CAP); Habitats Directive; EU Forest Strategy; EU Floods Directive; Health 2020 and the EU Adaptation Strategy.

1.3. Links to other work packages (WP)

The application of the climate change impact, adaptation and vulnerability (CCIAV) models within the European Case Study links to other parts of the IMPRESSIONS project:

- **WP1** – empirical research interviewing the case studies’ decision-makers to assess actual decision-making processes and information needs to ensure that scenarios, models and pathways are developed to: (i) meet the needs of decision-makers; and (ii) account for the actual (adaptation) decision-making patterns and behaviours of decision-makers;
- **WP2** - developing multi-scale, integrated climate and socio-economic scenarios, including high-end RCPs;
- **WP3A** – providing selected boundary conditions from the global scale RCPxSSP modelling;
- **WP3C** - providing selected results to augment the regional case studies;
- **WP4 and 5** – developing the time-dependent adaptation-mitigation-transformation pathways for achieving the stakeholder-identified vision for Europe which the European case study models will evaluate for the 3rd stakeholder workshop;
- **WP6A** – the European case study will have two workshops (WS#2 and WS#3 in the IMPRESSIONS workshop framework) and will contribute to a cross-scale workshop WS#ALL) which are supported by the modelling results.

2. Methodology for European scale CCIAM modelling in IMPRESSIONS

2.1. Scenarios

2.1.1. Climate scenarios, including model uncertainty

For use in IMPRESSIONS, a sub-set of climate model simulations were selected from CMIP5 to represent changes in global mean temperature ranging from less than 2°C to more than 4°C (Table 2.1). In order to benefit from the higher resolution of regional simulations, only GCM simulations that had been dynamically downscaled in CORDEX were included in the sub-set. This selection process is described in more detail in Deliverable D2.1 (Kok et al. 2015). In order to use the IAP2 to also explore impacts of very low-end climate change, the core set of scenarios was later extended with a set of scenarios representative of a global mean temperature change of 1.5°C as compared to pre-industrial conditions. These additional very low-end scenarios were added after the initial model selection and are included in the European IAP2 (not in rIAM). The climate model data used in the European IAP2 have been bias-adjusted using the Delta Change method as described in Deliverable D2.3 (Madsen et al. 2016).

Table 2.1: Details of the climate scenarios selected for use in IMPRESSIONS (table adapted from D2.3 [Madsen et al. 2016] but extended with the RCP2.6 scenarios). European change in temperature (ΔT) and precipitation (Δpr) is relative to 1961-1990.

Climate change	Emission scenario	GCM	RCM	GCM sensitivity	European $\Delta T/\Delta pr$
High	RCP8.5	HadGEM2-ES	RCA4	High	5.4°C / 5%
High	RCP8.5	CanESM2	CanRCM4	High	5.4°C / 8%
High	RCP8.5	IPSL-CM5A-MR	WRF	High	4.7°C / 13%
Intermediate	RCP8.5	GFDL-ESM2M	RCA4	Low	3.7°C / 6%
Intermediate	RCP4.5	HadGEM2-ES	RCA4	High	3.0°C / 3%
Low	RCP4.5	GFDL-ESM2M	RCA4	Low	2.2°C / 3%
Low	RCP4.5	MPI-ESM-LR	CCLM4	Low	2.0°C / -4%
Very low	RCP2.6	EC-Earth	RCA4	Intermediate	1.4°C / 4%
Very low	RCP2.6	GFDL-ESM2M	REMO	Low	1.3°C / 1%
Very low	RCP2.6	NorESM1-M	RCA4	Low	1.3°C / 4%

Figures 2.1 to 2.3 show maps of the climate change signal of temperature and precipitation (2071-2100 vs 1961-1990) for each of the RCP-GCM-RCM combinations.

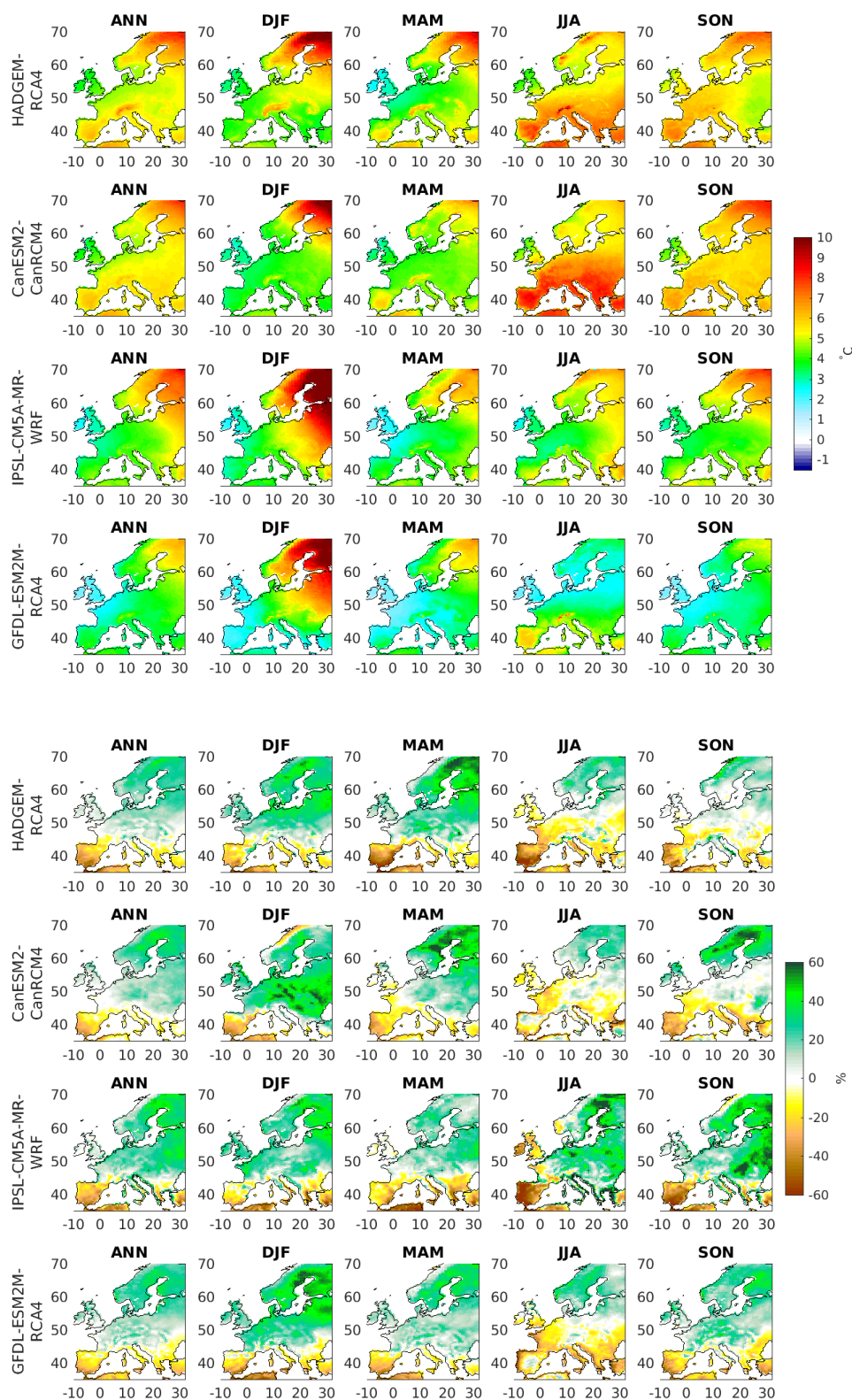


Figure 2.1: Annual and seasonal (upper) temperature and (lower) precipitation changes across Europe in 2071-2100 (relative to 1961-90) for the IMPRESSIONS GCM-RCM models under RCP8.5.

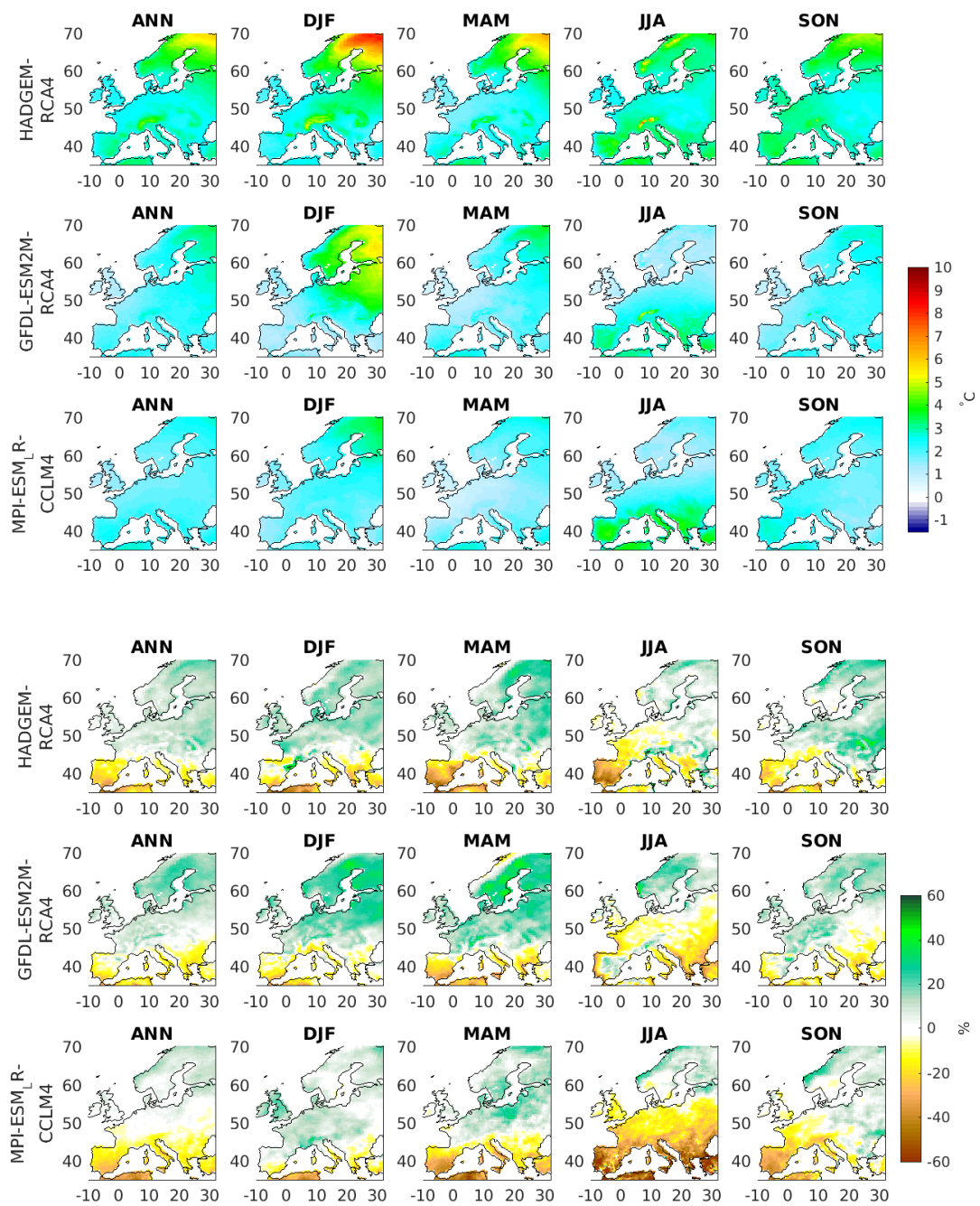


Figure 2.2: Annual and seasonal (upper) temperature and (lower) precipitation changes across Europe in 2071-2100 (relative to 1961-90) for the IMPRESSIONS GCM-RCM models under RCP4.5.

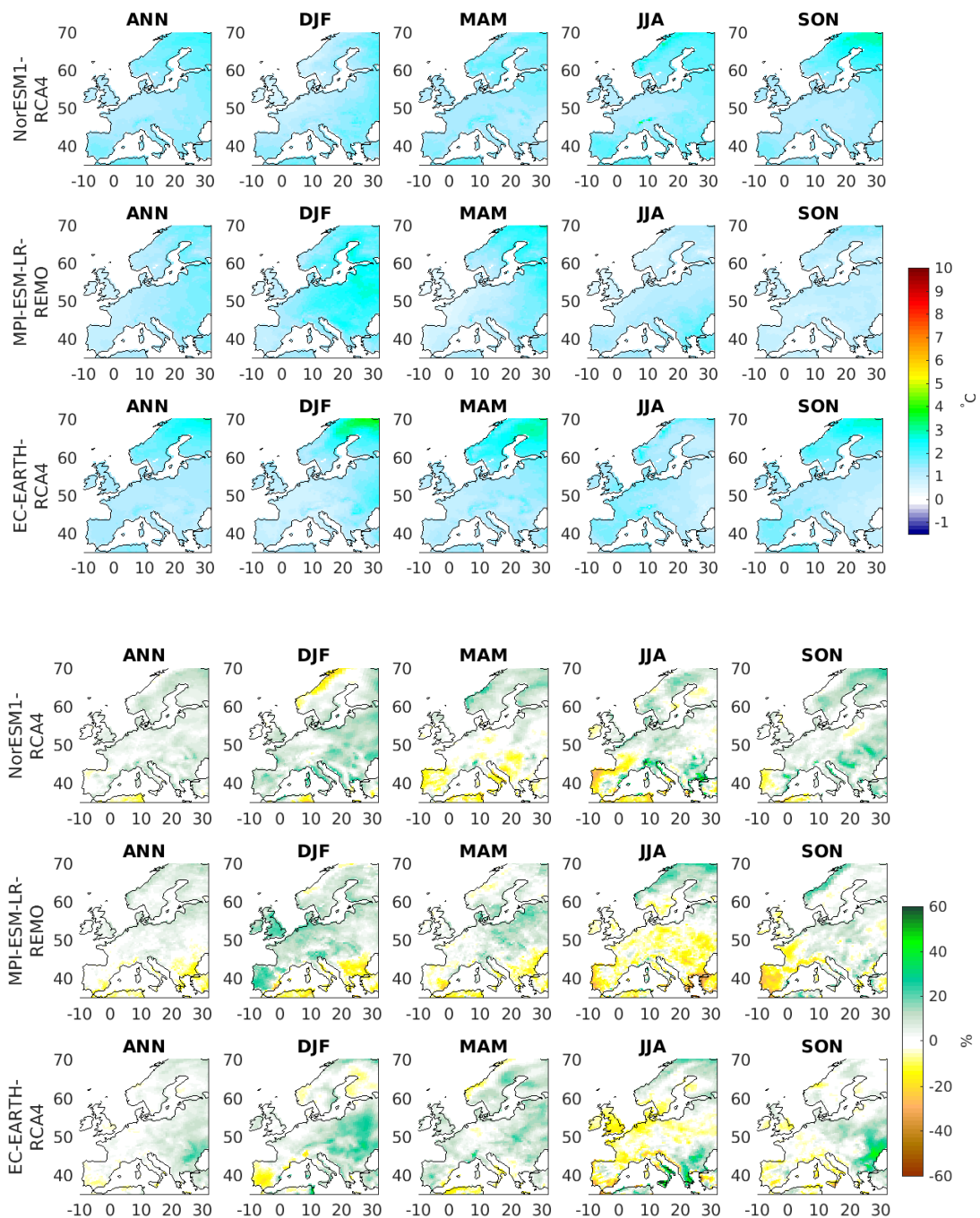


Figure 2.3: Annual and seasonal (upper) temperature and (lower) precipitation changes across Europe in 2071-2100 (relative to 1961-90) for the IMPRESSIONS GCM-RCM models under RCP2.6.

2.1.2. Socio-economic scenarios, including scenario quantification

The socio-economic scenarios are based on the Shared Socioeconomic Pathways (SSPs) logic in all case studies (described in Deliverable D2.1 - Kok et al. 2015). In the European case study the SSPs selection were partly derived from the earlier CLIMSAVE scenarios (Deliverable 2.1 - Kok et al. 2015; and Deliverable 2.2 - Kok and Pedde, 2016). Early in IMPRESSIONS, the decision was taken to limit the number of SSPs to be used in the participatory process to four (SSP1, SSP3, SSP4 and SSP5) for a variety

of reasons explained in Deliverable D2.1 (Kok et al. 2015). These four SSPs capture the low and high challenges to both mitigation and adaptation.

Deliverable D2.1 (Kok et al. 2015) describes how the four CLIMSAVE socio-economic scenarios were matched with these four global SSPs and extended until 2100 (Table 2.2). For the European case study, it proved difficult to match SSP5 (Fossil-fuelled Development) with the CLIMSAVE scenarios, so this scenario was developed based on the global SSP storyline. However, SSP1 (Sustainability) and SSP3 (Regional Rivalry) matched well and SSP4 (Inequality) matched in part, so elements of both scenario sets are being combined. In the case of mismatches between the SSP and CLIMSAVE scenario narratives, the global SSPs took precedence.

Table 2.2: CLIMSAVE scenarios for Europe with illustrative examples for economic, environmental and social uncertainties, and most similar SSP (adapted from Deliverable D2.1; Kok et al. 2015).

Scenario	Economic	Environmental	Social	SSP
We are the World	Gradual increase	Effective solutions	High social cohesion	SSP1
Icarus	Gradual decline	Ineffective solutions	Decline, then picking up	SSP3
Riders on the Storm	Rollercoaster downwards	Effective solutions	Low social cohesion	SSP4
Should I Stay or Should I go?	Rollercoaster up and down	Ineffective solutions	Low, but growing	No SSP equivalent

The match between global and European SSPs was decided to be ‘equivalent’, i.e. where outcomes can directly be transferred across scales (Kok et al. in prep. and Zurek & Henrichs 2007), for both qualitative descriptions and some key variables. The qualitative descriptions include short and generic narratives and tables which summarise trends in key elements. Quantified values of the key variables of GDP, population and urbanisation are provided in the global SSP database v1.0 hosted by IIASA (<https://secure.iiasa.ac.at/web-apps/ene/SspDb/>) and are used as model input and boundary conditions (see Section 2.3.3.). For quantification of other key model input variables, WP2 used a combination of expert estimates directly derived at a WP2 workshop (held in Wageningen in January 2015) and analysed using a ‘Fuzzy Sets’ based approach (Pedde et al. submitted) and WP3 modeller expert judgment. Thus, the global inputs to the pan-European modelling exercise (the global boundary conditions) were derived from the IIASA SSP database and outputs of the IMAGE model supplemented by expert judgement to ensure that the selected values were consistent with stakeholder and modeller expectations of the European SSPs.

2.1.3. Scenario integration

Deliverable 2.1 (Kok et al. 2015) describes the rationale for the selected high-end RCPxSSP combinations, which was to select a number of combinations of RCPs and SSPs that fulfil the following requirements:

- The RCPs are high-end;
- The SSPs cover a broad range of socio-economic developments;
- The SSPs relate to the CLIMSAVE scenarios;
- The combination of SSPs and RCPs are plausible (or at least not impossible), meaningful and useful;
- The set of combinations covers a range of (high-end) future outlooks.

Following a request from the European Commission following the Paris Agreement, the first criterion was modified to allow the inclusion of RCP2.6. In addition, for the purposes of the stakeholder workshops and this report, a default GCM-RCM was identified for each scenario combination (Table 2.3), although all climate models have been simulated to provide an understanding of the importance of climate model uncertainty.

Table 2.3: Final selected high-end and low-end scenario combinations and default climate model.

Shared Socio-economic Pathway (SSP)	Representative Concentration Pathway (RCP)	GCM	RCM
SSP5	RCP8.5	HadGEM2-ES	RCA4
SSP3	RCP8.5	HadGEM2-ES	RCA4
SSP3	RCP4.5	HadGEM2-ES	RCA4
SSP4	RCP4.5	HadGEM2-ES	RCA4
SSP1	RCP4.5	HadGEM2-ES	RCA4
SSP1	RCP2.6	EC-Earth	RCA4
SSP4	RCP2.6	EC-Earth	RCA4

2.2. IMPRESSIONS' CCIIV models within the European case study

A diverse range of models have been applied within the European case study to simulate the impacts of vulnerability to, and adaptation to, climate and socio-economic change, which are briefly described in the following sections. In order to ensure that decision-maker relevance is taken account in the model development (Dzebo et al. 2015), the model indicators have been mapped with WP1 against the identified high-level objectives for the identified EU policies or strategies in Section 1.2 (Table 2.4).

2.2.1. Integrated models

Two integrated modelling platforms have been developed and applied within the European case study – the IMPRESSIONS Integrated Assessment Platform (IAP2) and the European regional Integrated Assessment Model (rIAM) which are both further developments of the CLIMSAVE Integrated Assessment Platform (IAP1; Holman and Harrison 2012; Harrison et al. 2015). The principal difference between the two platforms (outlined in Holman et al. 2015) is the treatment of time, with the rIAM having an automated time-stepping approach whereas the IAP2 runs on time-slices with the user moving between time-slices. Both platforms contain a similar series of linked sectoral models (Figure 2.4) which are described in Holman et al. (2015) but are briefly summarised here:

- Urban: The Regional Urban Growth (RUG) meta-model (based on Reginster and Rounsevell 2006) simulates the change in artificial surfaces for each NUTS2 region as a function of changes in the population (total) and GDP (per capita), societal preferences (proximity to green space versus social amenities, and attractiveness of the coast) and strictness of the planning regulations to limit sprawl, assuming a fixed ratio of residential to non-residential urban areas. This function was calibrated from historical observational data across Europe. The IAP2 version has been further developed within rIAM to reflect how changing population structure might influence preferences for different residential types (Fontaine et al. 2014).

Table 2.4: Mapping of European case study model outputs to high-level policy objectives.

[illegible]

- **Health:** The HEET model simulates annual heat-related mortality attributable to climate change, by age group and by sub-region, based on a counterfactual of no warming across Europe. Heat-related mortality is quantified for three age-groups (0-64, 65-74, 75+) as risk increases greatly with age. Future baseline mortality is estimated based on the all-cause mortality projections that have been produced for the SSPs (Lutz et al. 2014). New exposure response functions based on the model developed by Gasparrini et al. (2010) have been developed which better characterise the population response at the extreme end of the (exposure) temperature distribution, in order to capture the uncertainty in assessing impacts under high-end scenarios.
- **Water:** The WaterGAP (WGMM) meta-model (Wimmer et al. 2015) uses 3D response surfaces to reproduce WaterGAP3 (Floerke et al., 2013). It runs at a 5' x 5' resolution for about 100 spatial units (single large river basins or clusters of smaller, neighbouring river basins with similar hydro-geographic properties). The difference between simulated water availability (based on average river discharge Q_{avg}) and projected non-agricultural water consumption determines the maximum water available for agricultural irrigation in each spatial unit.
- **Flooding:** The Coastal Fluvial Flood (CFFlood) meta-model (Mokrech et al. 2015) is a simplified process-based model that identifies the area at risk of flooding based on topography, relative sea-level rise or change in peak river flow (derived using the median annual maximum flood discharge or Q_{MED} from WGMM) and the estimated Standard of Protection of flood defences. The probability of flood inundation constrains the allocation of land for agriculture, with land with a > 10% and > 50% annual probability of flooding being unsuitable for intensive agriculture and extensive agriculture, respectively, according to Mokrech et al. (2008).
- **Forest:** MetaGOTILWA+ (Audsley et al. 2015) is an artificial neural network (ANN) that emulates GOTILWA+ (Gracia et al. 1999). The ANN was trained on GOTILWA results for 889 grid cells across Europe, and simulates average timber yields for a range of deciduous and coniferous tree species under different management regimes and soil characteristics. In the rIAM, this model has been replaced by a meta-model of ForCLIM (Bugmann 1996) to better represent northern tree species and the potential for changes in species selection as a consequence of high-end scenarios.
- **Crops:** The crop yield meta-models (Audsley et al. 2015) predict the average yield of a range of annual and permanent crops under rainfed and irrigated conditions. Those in the IAP2 have each been trained and validated on simulated outputs across Europe from the daily ROIMPEL model (Audsley et al. 2006) for winter and spring wheat, barley and oilseed rape, potatoes, maize, sunflower, soya, cotton, grass and olives. These have been augmented in rIAM by the inclusion of additional crop yield meta-models derived from simulations of Yield-SAFE, a process-based model used to predict long-term crop yields (Van de Werf et al. 2007; Graves et al. 2010).
- **Rural land allocation:** The SFARMOD meta-model (Audsley et al. 2015) allocates available land across Europe based on profit and other constraints (urban land use, irrigation availability, food and timber demand). It uses a series of regression equations to simulate the behaviour of the full SFARMOD-LP model, a mechanistic farm-based optimising linear programming model of long-term strategic land use. The meta-model was fitted to SFARMOD-LP outputs from 20,000 randomly selected sets of input data that fully cover the current and future parameter input space. In the rIAM, this model has been further developed to recognise the barriers and timelags in land use change, so that only a proportion of change to a new land uses occurs within a given timestep.
- **Biodiversity and habitats:** The CFFlood meta-model (Mokrech et al. 2015) also simulates: change/loss in inland and coastal (inter-tidal, saltmarsh and coastal grazing marsh) habitats

due to future climate and socio-economic conditions. The SPECIES model (Spatial Estimator of the Climate Impacts on the Envelope of Species) (Harrison et al. 2006) simulates the suitable climate space of over 100 species selected to interact with the agricultural, forest, coastal and water sectors and to indicate a range of ecosystem services; and evaluates the changing presence of appropriate conditions for a given species provided by appropriate climate space and appropriate climate and habitat space.

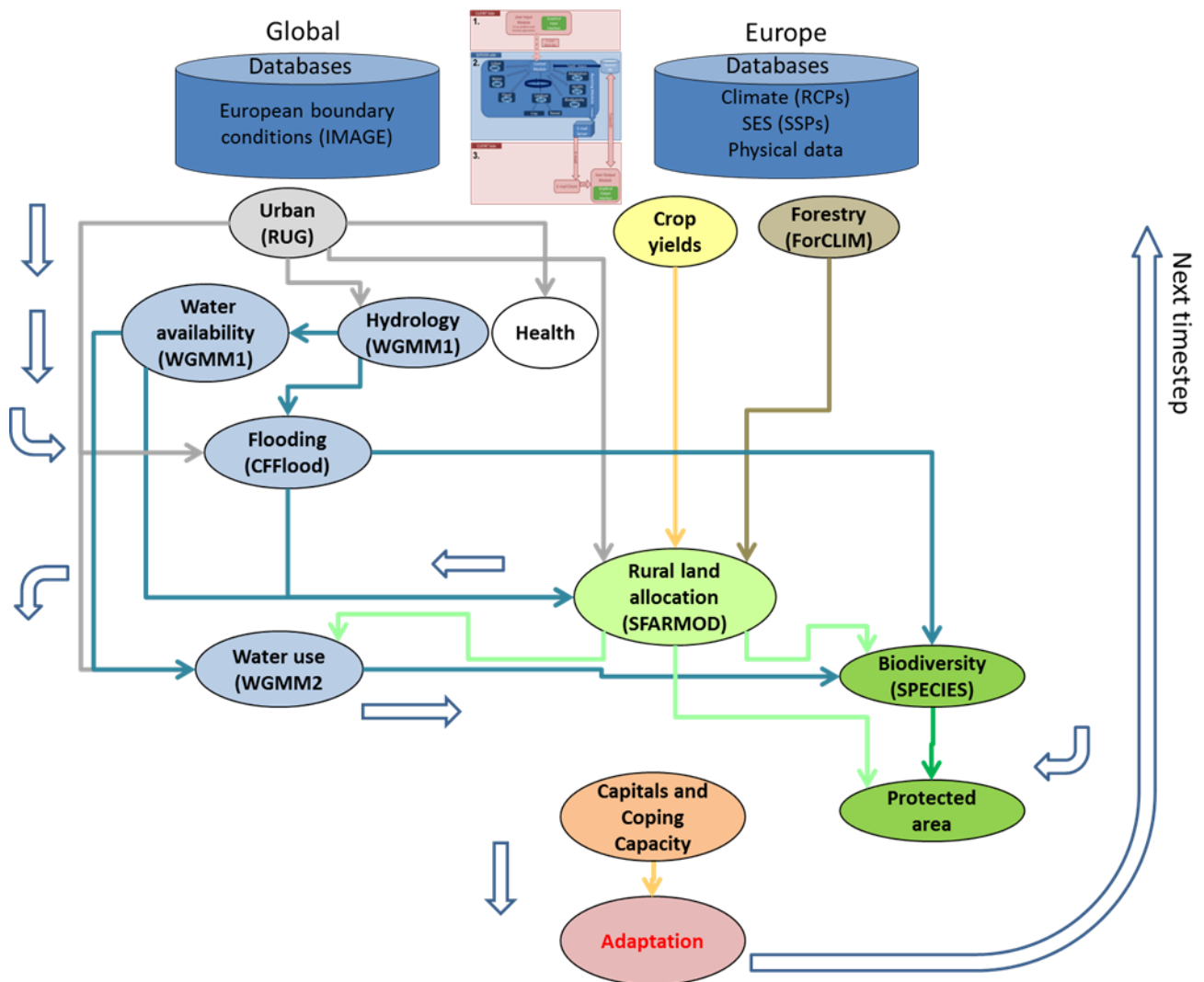


Figure 2.4: Simplified draft schematic of the linkages between the various meta-models (ovals) of the European IAP2 and rIAM integrated modelling platforms (NB: Health is not included within the IAP2).

2.2.2. Physically-based models

The Soil and Water Integrated Model (SWIM; Krysanova et al. 1998; Figure 2.5) is a process-based deterministic eco-hydrological model, developed from two previous models: SWAT and MATSALU. It enables representation of the components of the hydrological cycle and related processes at the river basin scale. SWIM has been set-up for a set of representative river basins across Europe (Figure 2.6 and Table A1.1), selected to link to the regional case studies of WP3C (Scotland, Hungary and Iberia), and to also include the different geographical regions across Europe. The SWIM model was set-up,

calibrated and validated for all seven basins using the WATCH Era Interim dataset (Weedon et al. 2014) as climate input for the historical period. The river discharge in future periods was simulated with the SWIM model driven by the coupled GCM-RCM climate projections, described in detail in Deliverable D2.3 (Madsen et al. 2016). The climate projections were bias-corrected to the WATCH Era Interim dataset. The SWIM model description was provided in Deliverable D3B.1 (European modelling specification - Holman et al. 2015), as well as in D3C.1 (Regional modelling specification – Rounsevell et al. 2015).

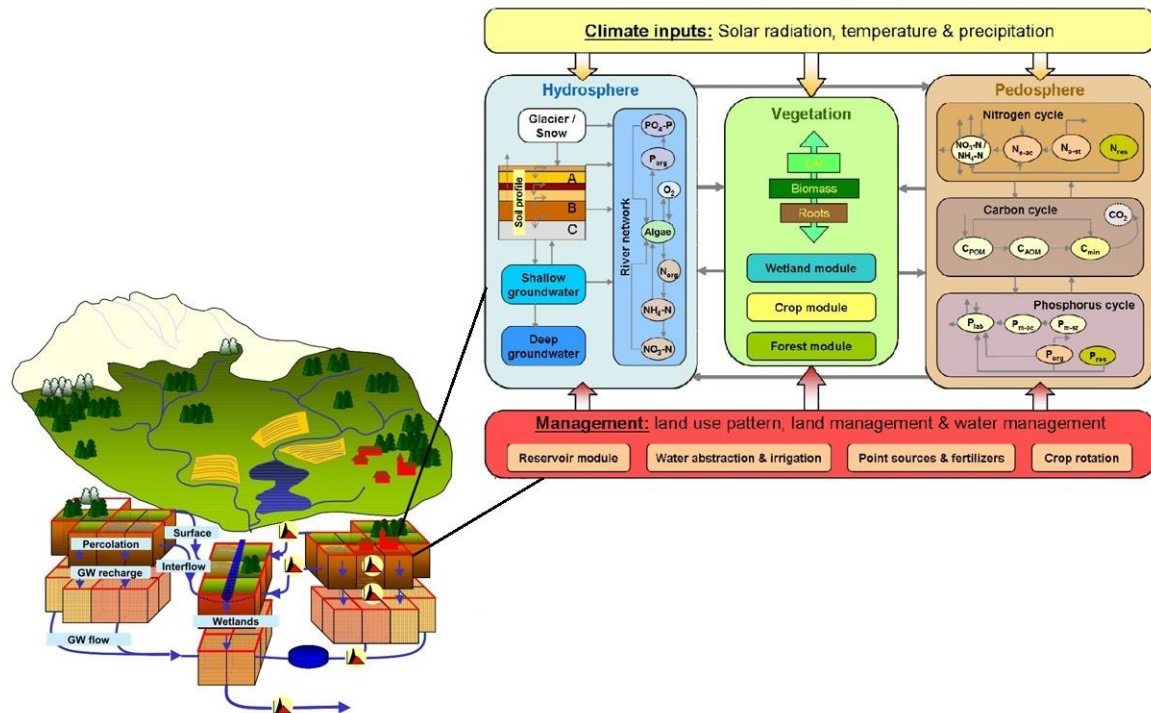


Figure 2.5: Schematic representation of the SWIM eco-hydrological model.

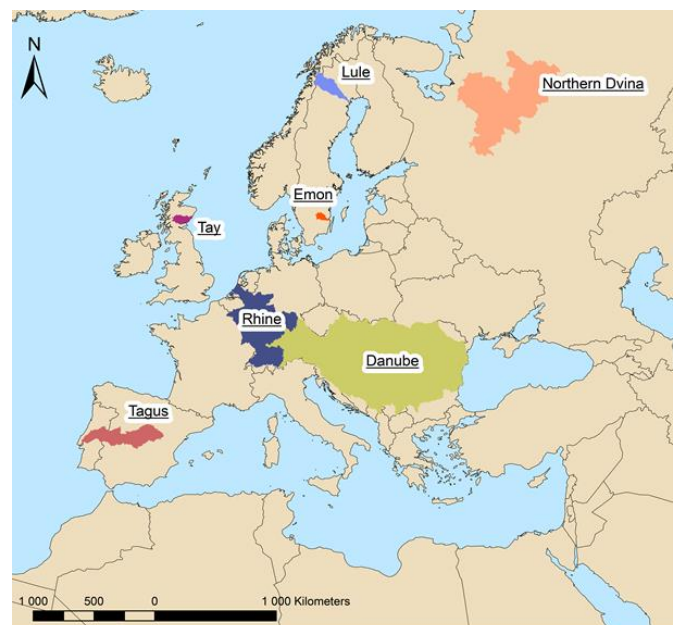


Figure 2.6: The representative river basins being simulated by the SWIM process-based model within the European case study.

The baseline model performance during calibration and validation periods, using the Nash-Sutcliffe efficiency (NSE) (Nash & Sutcliffe 1970) and the Relative Volume Error (RVE), are given in Table A1.2 and demonstrate acceptable (e.g. for the Rhine river) to very good (e.g. Dvina river) performance using the classification of Moriasi et al. (2007).

The SWIM model provides additional detailed information on climate change impacts on hydrology, compared to that provided by WGMM and CFFlood. The reliability of the representation of hydrological changes in WGMM can therefore be tested by comparison with results for Q_{avg} and Q_{MED} from SWIM for the three large river basins of Danube, Rhine and Tagus

2.2.3. Agent-based models

The CRAFTY Agent-Based Model (ABM) of land use change (Figure 2.7) simulates European land use dynamics under a range of scenarios, governance strategies and institutional interventions in order to explore development of the European land system. CRAFTY operates at the European scale on the basis of exogenous climatic, socio-economic and demographic drivers of land use change, and the behaviour and decision-making of institutions and individual land managers (modelled as autonomous agents).

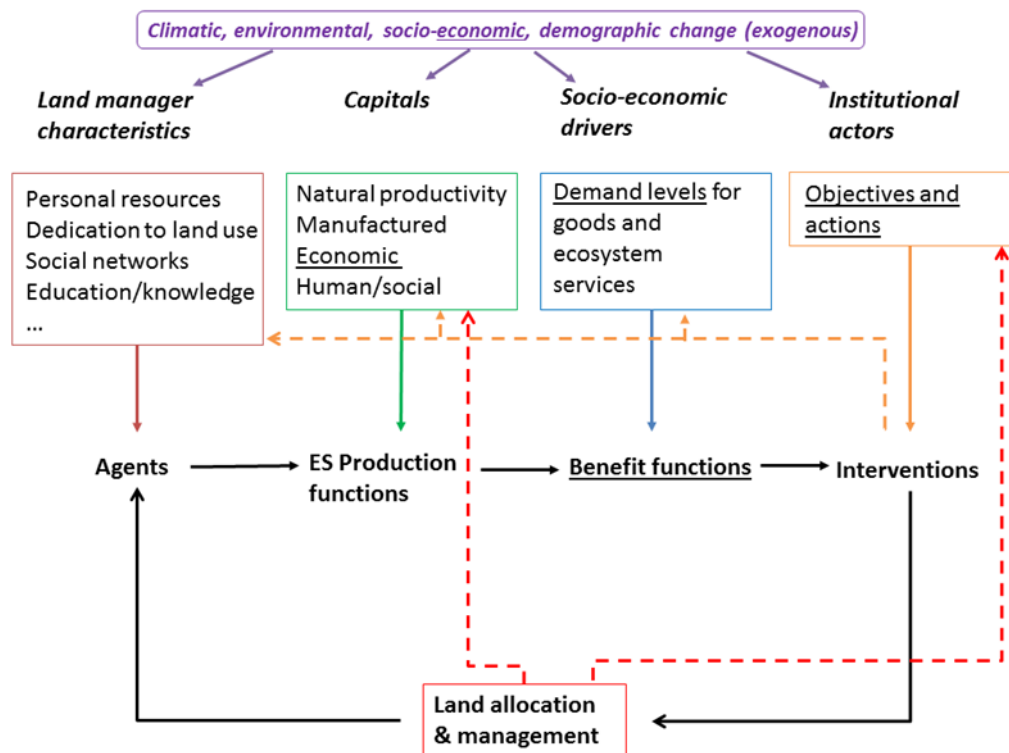


Figure 2.7: Schematic of the CRAFTY model. Inputs fall under four broad categories (top) and influence modelled processes at the points shown. Underlined terms indicate inputs from WP5 models (see D5.2 New family of ABMs). Agents are parameterised on the basis of census, literature and social survey data, and their ability to produce ecosystem services is defined via capitals describing potential productivity and observed production levels. The benefits or utilities of production depend upon the sizes, scales and forms of societal demands for ecosystem services. Institutions intervene at various stages in the modelled process and monitor subsequent changes in land management and service production. They also affect particular capital levels, which subsequently affect land use decisions. The solid black arrows represent model flow during one simulated time-step, set to the duration of land management decision-making (e.g. one year). Exogenous (scenario-based) changes impact upon the model at each stage and time-step.

Institutions primarily interact with land manager agents by disseminating knowledge and technology through social networks, by subsidising or proscribing certain land uses or land use transitions, and by altering levels of demand for particular ecosystem services. Both land manager and institutional agents respond to climate change as expressed through its effects on the productive potential of the land, and therefore on the ability of the land system to satisfy human requirements for ecosystem services. The land manager agents differ in terms of their ability to produce ecosystem services, sensitivity to profit, dedication to their land use, social network connections, willingness to adopt innovations and a number of other personal and cultural factors that can be varied depending on model context and objectives.

2.3. Simulating progress towards a Vision for Europe under high-end scenarios

In collaboration with WP4 and 5, the European case study has evaluated the potential for adaptation, mitigation and transformative actions to move Europe towards a desired end-point in the face of the challenges of high-end climate change. This has involved a number of stages (Figure 2.8):

- Prior to the second European stakeholder workshop, the stakeholder attendees were asked to characterise their desirable vision for Europe in 2100. These individual Visions were combined into a draft Vision (Box 2.1) through a process described in D4.1 (Frantzeskaki et al. 2015).
- Within the second European stakeholder workshop, the draft Vision (including any omissions from individual visions) was discussed by the stakeholders and a final Vision for 2100 agreed. This Vision represents the desired end goal (#2 in Figure 2.8 below) against which the "success" of stakeholders' adaptation / mitigation / transformation pathways can be assessed. The focus of the transformative vision is explicitly set to 'where we want to be' and not to 'where we are heading now' or 'how to go there'.
- Subsequently at the second European stakeholder workshop, selected impact and vulnerability results from the European modelling were presented illustrating the consequence of each of the integrated RCPxSSP combinations (i.e. moving from #1 to #3 in Figure 2.8 below).
- In response to the differences between aspects of #3 and their Vision (#2), the stakeholders identified a range of adaptation, mitigation and transformation actions (#4) that they thought would move the scenario future nearer (#5) to the Vision.
- These adaptation, mitigation and transformation actions were structured into a set of coherent strategies and pathways for each SSP by WP4, and a questionnaire survey circulated to workshop participants to confirm the outcomes of this process.
- Qualitative and quantitative approaches have then been applied to assess how far #5 is from the Vision so that the stakeholders can identify additional actions (#6) at the third stakeholder workshop.

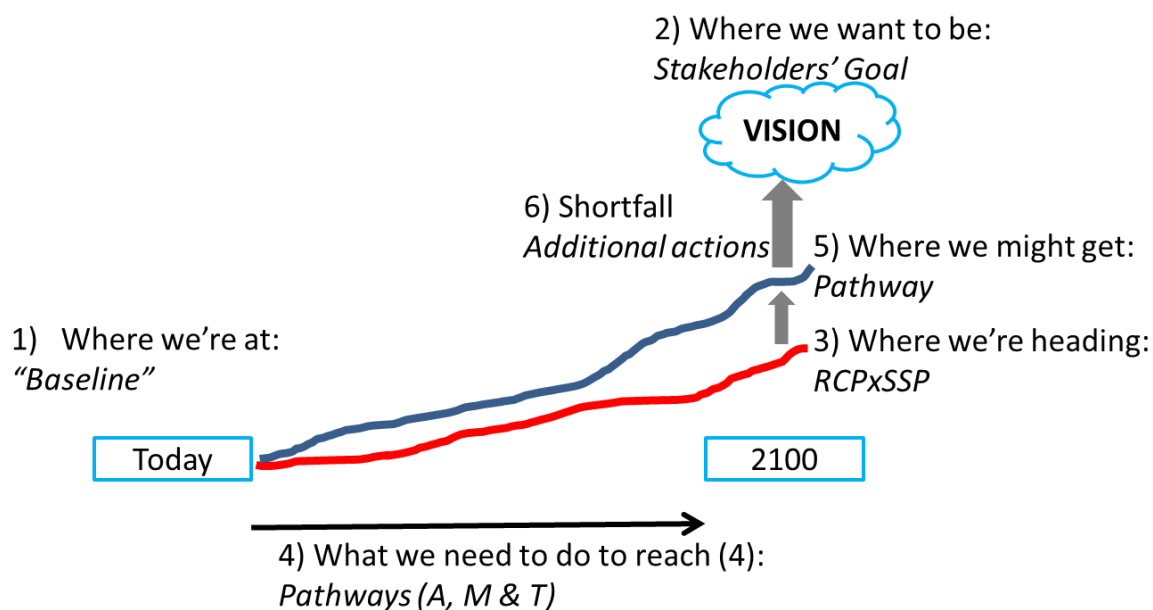


Figure 2.8: Schematic illustration of the relationships between the modelling, Visions and Pathways.

Box 2.1: Key elements of the IMPRESSIONS stakeholders' Vision of the European Union in 2100.

Living and lifestyles

- High quality of life
- Healthy
- Self-sufficient communities
- High-density living
- Basic human needs met
- Solidarity
- Advanced and affordable education

Voice, equity and equality

- Equity among citizens and societies
- Wealth duly distributed
- Poverty eradicated

Governance

- New modes of governance
- Democratic values
- Europe is strong, peaceful and cohesive
- National and regional diversity
- Collective goals
- Unified in the face of challenges

Environment

- Balance in preserving and using ecosystem services
- CO₂ concentration stabilised at 450 ppm CO₂ eq.
- Respect planetary boundaries
- Resources used efficiently

Food, water and energy

- Zero CO₂ emissions
- High dependence on renewable energy sources
- Sustainable agriculture and fisheries
- Food security for all
- Sustainable use of water

Resilience

- Acting pre-emptively
- Striving to prevent crises
- Disaster risk plans widely available

The stakeholders' Vision for Europe in 2100 contains a diverse range of elements, some of which can be related to modelled indicators, but many which cannot. As a consequence, a twin-track approach was used to enable quantitative (model-based) and qualitative (expert-based) analyses of the pathways to be integrated, as shown in Figure 2.9 and described in Table 2.5.

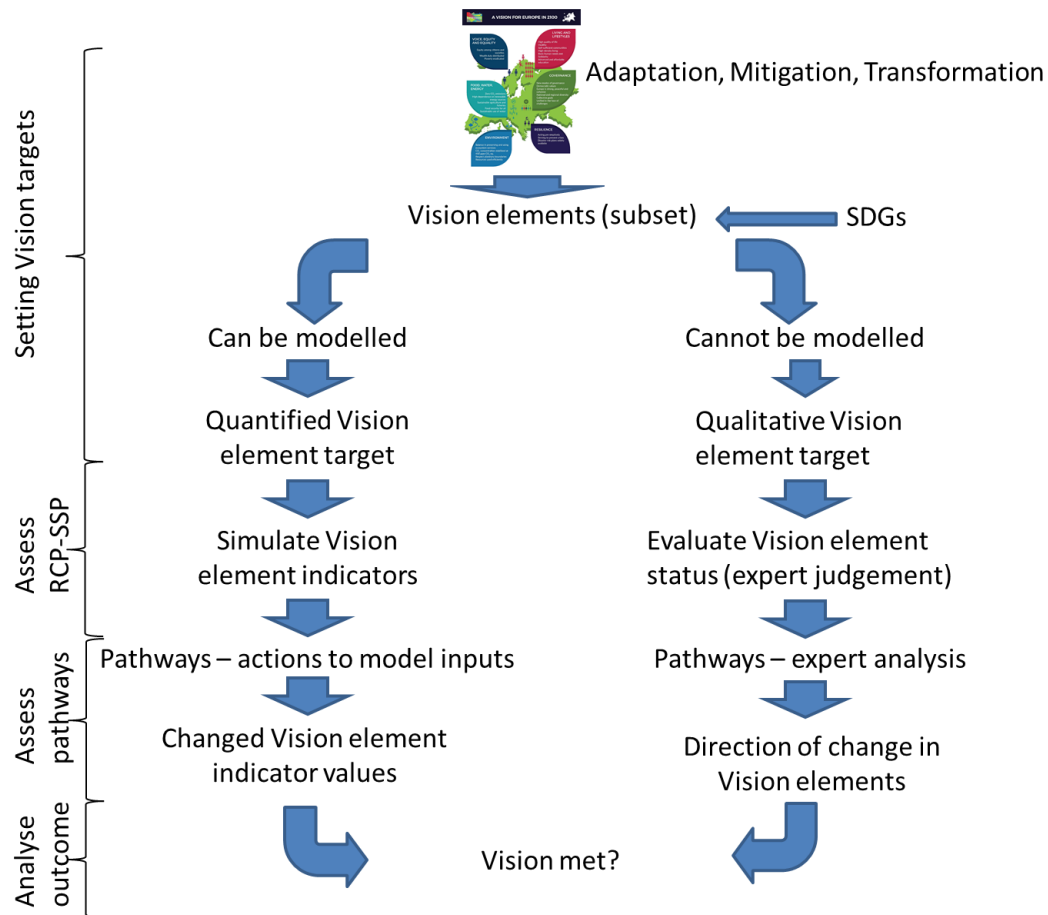


Figure 2.9: Overview of framework for evaluating the pathways in each individual RCPxSSP combination against the Vision.

Table 2.5: The stages of integrating the stakeholder Vision, impacts/vulnerability modelling and adaptation, mitigation and transformation pathways.

Stage	Quantitative Track	Qualitative track
1) Setting Vision targets	The Vision elements were classified according to whether they are likely to either necessitate adaptation, mitigation and/or transformation to achieve them	
	A sub-set of Vision elements were identified for the analysis [<i>related SDGs and indicators were used to identify key elements within the Vision</i>]	
	For each vision element that can be related to a model indicator, expert judgement was used to derive a quantified value or threshold which would demonstrate whether the Vision element has been achieved	For each vision element that cannot be related to a model indicator, an additional qualitative description of the vision element was added (through expert judgement) to help characterise whether it has been achieved
2) Assessing each RCP-SSP scenario against Vision elements	CCIAV models were run to assess whether a scenario achieves this value by 2100	Expert judgement, taking account of scenario narrative, constraints and available RCPxSSP model results, were used to assess whether the desired status of the qualitative vision elements are met by 2100
3) Assessing the pathways for a given RCP-SSP scenario	Looking across all pathways, actions were identified within each time period that would affect, either individually or in aggregate, model inputs in a particular direction (increase / decrease). <i>For example, actions of “Invest in agricultural and water innovation to improve productivity” and “Invest in innovation in food production for food security” might lead to increases in model input values set for ‘irrigation efficiency’, ‘mechanisation’ and ‘yield improvement’ and also might decrease ‘fertiliser’ use.</i>	Looking across all pathways, actions were identified within each time period that would affect, either individually or in aggregate, each qualitative vision element
	Model input values changed to represent the maximum amount of change that is credible within the scenario context	
	The model(s) were run to assess whether the target value is achieved for each modelled Vision element by 2100	Expert judgement is used to assess whether the actions are likely to move the status of the vision element closer to the desired status by 2100
4) Analyse outcomes	The consequences of the pathways for achieving the Vision by 2100 for a given RCPxSSP were evaluated, considering: - the quantitative and qualitative analyses of vision elements; - synergies and trade-offs identified during the analysis; - key vision elements that appear not to be met through the actions within the current pathways; - the balance between adaptation, mitigation and transformative actions within the pathways; and the relative needs of each identified across the whole Vision identified in the 1st step.	

3. Future impacts and vulnerability

This section examines the impacts and vulnerability on land use, human wellbeing, water and biodiversity in Europe across the range of SSP, RCP and GCM-RCM combinations within IMPRESSIONS according to Table 2.3. Whilst EC-Earth_RCA4 has been used for RCP2.6 and HadGEM2-ES_RCA4 has been used for RCP4.5 and 8.5 as the default climate model in the simulations presented, selected examples from using other GCM-RCM combinations are presented to demonstrate the consequences of climate model uncertainty under high-end scenarios.

3.1. Land cover and land use

This section explores how land cover (the physical cover or vegetation type) and land use (the activities undertaken on the land) might respond to high-end climate change (RCP4.5 and RCP8.5). This change is placed within the context of multiple socio-economic scenarios (SSPs). Broad-scale European land use change is explored via two modelling approaches, firstly, the IMPRESSIONS integrated assessment platform (IAP2), and secondly, an agent-based model (CRAFTY). After considering broad-scale patterns, more detailed results are reported for forest productivity and urban land use modelling.

3.1.1. Trends in European land use change within high-end climate change scenarios: Integrated modelling approaches

Two analyses have been used to explore the response of European land use to high-end climate change using the IMPRESSIONS integrated assessment platform (IAP2):

- (i) a **scenario-neutral approach** that shows the modelled system response across a range of temperature and precipitation changes, allowing the production of Impact Response Surfaces (IRS);
- (ii) a **scenario-based approach** covering the WP2 climate change scenarios with baseline socio-economics (climate change only) and with the European SSPs.

In both, the IMPRESSIONS IAP2 simulates the responses of eight main land use types to changes in drivers that affect production and/or demand:

- **Urban** - the total extent of housing, commercial and industrial land use;
- **Arable** - arable and horticultural production and the land used for cereal fodder for cattle (for example, forage maize), indoor-housed animals and poultry (cereals);
- **Intensive grassland** - areas used for grassland production to support dairy herds and forage-fed intensive beef cattle;
- **Extensive grassland** - areas used for grassland production to support beef and sheep;
- **Very extensive grassland** - marginal land that is used for low intensity sheep grazing;
- **Managed forest** - forest and woodland that is used for commercial timber and wood production;
- **Unmanaged forest** - forest and woodland that is either used for non-commercial activities (for example, recreational use) or land in which woodland establishes due to natural succession;
- **Unmanaged land** - remaining land which does not support agricultural uses due to constraints (slope, soil depth, wetness) and in which woodland does not naturally become established.

In the scenario-neutral approach, the integrated model has been systematically run with perturbations applied to the baseline climate across Europe. The annual temperature perturbations range from -1°C to +11°C with intervals of 1°C, between -1°C and 5°C, and 2°C, between 5°C and 11°C;

whilst annual precipitation is perturbed between -60% and 40% at intervals of 10%. The modelled changes (assuming atmospheric CO₂, population and other socio-economic drivers are kept constant) are presented as regional aggregated IRS for eight European sub-regions (Figure 3.1).

Large changes in annual temperature only lead to significant simulated reductions in the proportion of intensive agricultural land and forest in southern Europe which is replaced by extensive grassland and unmanaged (abandoned) land. This arises as agricultural land loses relative profitability compared to (mostly) northern European regions, due to increased droughtiness, heat stress and water resource limitations, and forested areas become less climatically suitable. However, the agricultural area increases in most regions of Europe when large changes in annual temperature are combined with large reductions in precipitation. This apparently counter-intuitive result arises from the autonomous adaptation within the IAP2 which expands the European agricultural area, in the face of reduced climatic suitability and therefore reduced productivity across Europe, in order to meet food demand.

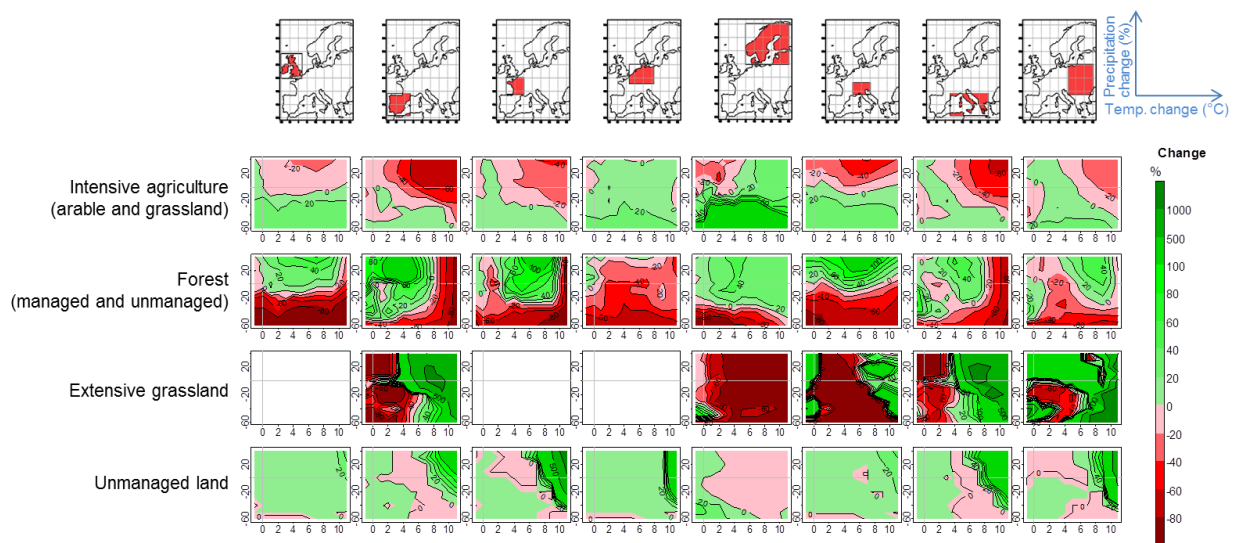


Figure 3.1: Simulated Impact Response Surfaces for land use changes in European regions arising from systematic modifications to annual average climate within the IMPRESSIONS IAP2.

Figure 3.2 shows the consequences of combined scenarios of climate and/or socio-economic change on aggregate European land uses classes according to the IAP2 using a default GCM-RCM for each RCP. The top row of Figure 3.2 shows the effects of climate change alone on the total area of the modelled land use types, whilst maintaining baseline socio-economics. In this case, the net food and timber demand for Europe remains constant over time and between the climate scenarios. Changes in managed agricultural and forest land use extent arise as climatically-driven changes in productivity increase or decrease the need for land to meet demand, respectively. The graphs show that the magnitude of the changes in European land use increase with increasing climate change and over time, although they are relatively minor at this aggregated scale. In particular, the total managed forest area simulated by metaGOTILWA decreases under the higher atmospheric CO₂ levels of RCP8.5, as increases in managed forest yield (due to CO₂ fertilisation) require a smaller forest area to meet timber and wood demand. However, the consequence of high-end climate change become apparent in the 2080s under RCP8.5, where there is an increase in unmanaged land, that is, land that is both not needed for productive uses such as food and timber and in which woodland won't naturally establish.

This indicates that the climate is becoming unsuitable for the modelled tree species within marginal land.

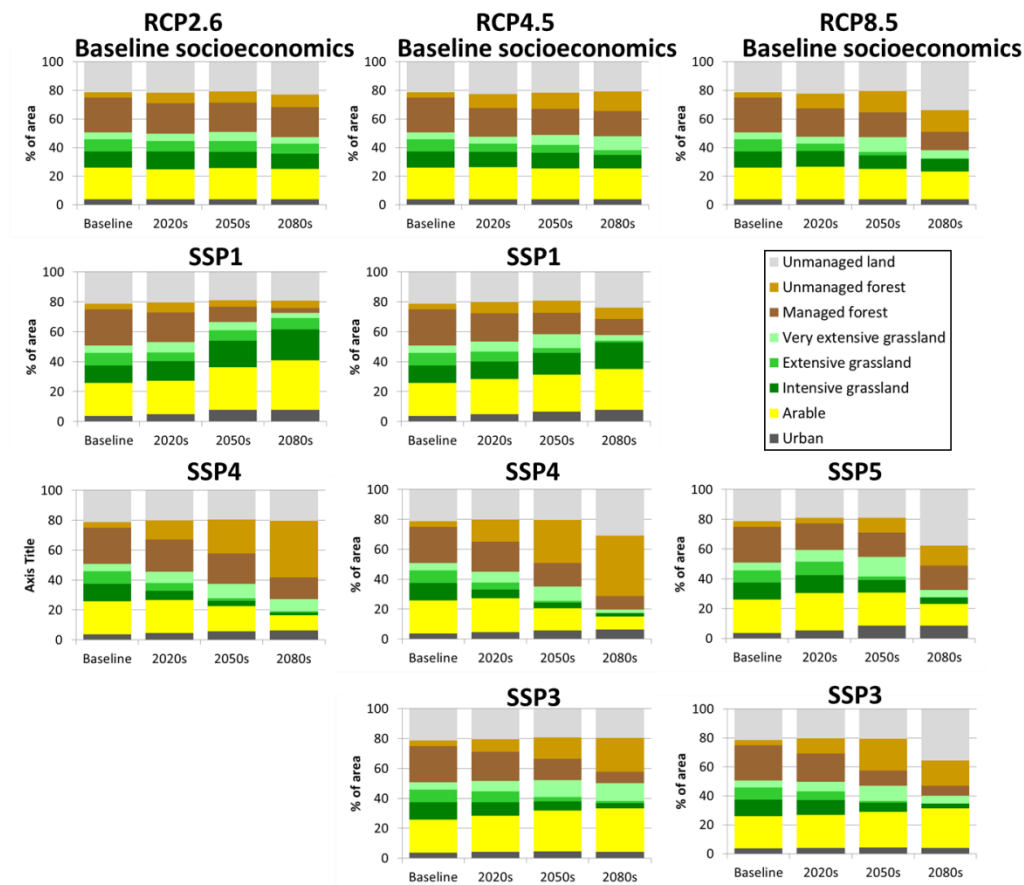


Figure 3.2: Simulated European land use proportions for multiple combinations of climate and socio-economic scenarios using the IMPRESSIONS IAP2.

With the introduction of the European SSPs (Figure 3.2; rows 2 to 4), there are a greater diversity of land use futures due to the additional interacting consequences of changing food and timber demand (due to population and GDP change), changing meat demand (due to dietary preferences), changing imports and changes in agricultural productivity associated with different levels of technological innovation. In particular:

- The European SSP1 is associated with a transition to organic and lower productivity agricultural systems that deliver multiple ecosystem services. As a consequence, the agricultural area expands to meet demand leading to major losses of forest area under RCP2.6 to the extent that demand for timber and wood cannot be met. Although this scenario is associated with reduced meat demand and increased vegetarianism, an associated increased demand for dairy products increases the area of intensive grassland systems. The higher CO₂ levels in RCP4.5 partially offset these increases.
- The European SSP5 is associated with effective innovation (that increases agricultural productivity) and an increased reliance on global free markets and associated food imports. As a consequence, these gradually offset food demand increases (due to increases in population and wealth) so that agricultural land uses peak in the 2020s and then decrease to the 2080s.

- The European SSP3 leads to relatively minor changes in land use, apart from the reduction in managed forest area. This arises as the decreased food demand due to the continually declining European population (-38% by the 2080s) are matched by decreased imports in this fragmented world and reduced agricultural productivity. There is relatively little difference between this SSP under the two RCPs as the effects of the socio-economic drivers outweigh the climate drivers at the European scale.
- In European SSP4, a declining population (-22% by the 2080s) combined with increased imports and agricultural productivity lead to a steadily declining agricultural area.

Climate model uncertainty also affects the changes outlined. The IMPRESSIONS IAP2 contains a choice of GCM-RCM climate scenarios for each RCP; three for RCP2.6 (EC-Earth / RCA4; MPI-ESM-LR / REMO; and NorESM1-M / RCA4), three for RCP4.5 (HadGEM2-ES / RCA4; MPI-ESM-LR / CCLM4; and GFDL-ESM2M / RCA4) and four for RCP8.5 (HadGEM2-ES / RCA4; CanESM2 / CanRCM4; IPSL-CM5A-MR / WRF; and GFDL-ESM2M / RCA4). Figure 3.3 shows the absolute range in the European percentage of each land use class between the different climate models. The magnitude of the uncertainty introduced is generally smaller than the differences between scenarios and time (Figure 3.3), although, it increases over time for a number of the land uses reaching over 14% for unmanaged land. The urban land use type is unaffected by the climate, hence the absence of climate model uncertainty. The aggregate European land use for each of the different climate models is given in the Appendix in Figure A1.1.

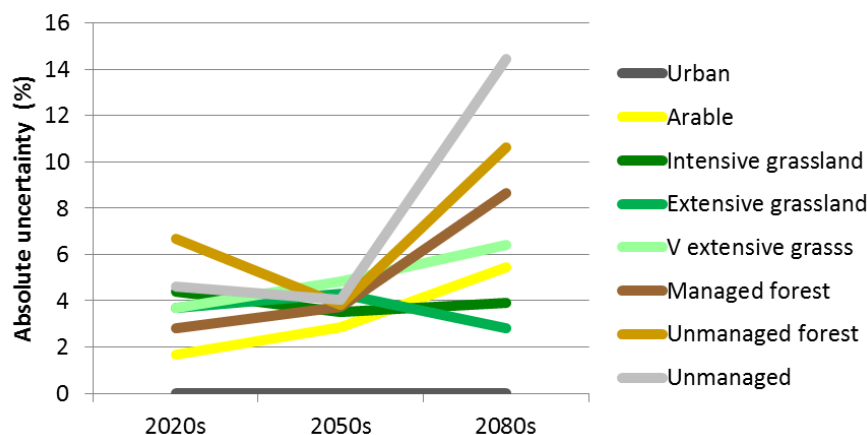


Figure 3.3: Maximum simulated uncertainty in European land use proportions due to climate model uncertainty across the multiple combinations of climate and socio-economic scenario using the IMPRESSIONS IAP2.

3.1.2. Trends in European land use change within high-end climate change scenarios: Agent-based modelling approaches

The CRAFTY (Competition for Resources between Agent Functional Types) agent-based modelling framework was used to simulate European land use change under the RCPxSSP scenario combinations (using the newly-developed CRAFTY-EU application). For this purpose, CRAFTY-EU was calibrated with output data from the IMPRESSIONS IAP2, so that common scenario conditions underlay both models. A set of European Agent Functional Types (AFTs; Murray-Rust et al. 2014; Arneth et al. 2014) was defined to allow comparison between CRAFTY-EU and the IAP2 while capturing major differences in the intensity and multi-functionality of land uses (Figure 3.4). Due to the relatively coarse resolution of the IAP2 grid, these AFTs were designed to represent both single and mixed land uses, accounting for the aggregate behaviour of land managers within these categories. CRAFTY-EU land use projections

are then based on the simulated decision-making of these managers, rather than overall optimum or equilibrium calculations. As a result, the supply of services is not constrained to meet demand, and supply can be generated through a variety of land use configurations.

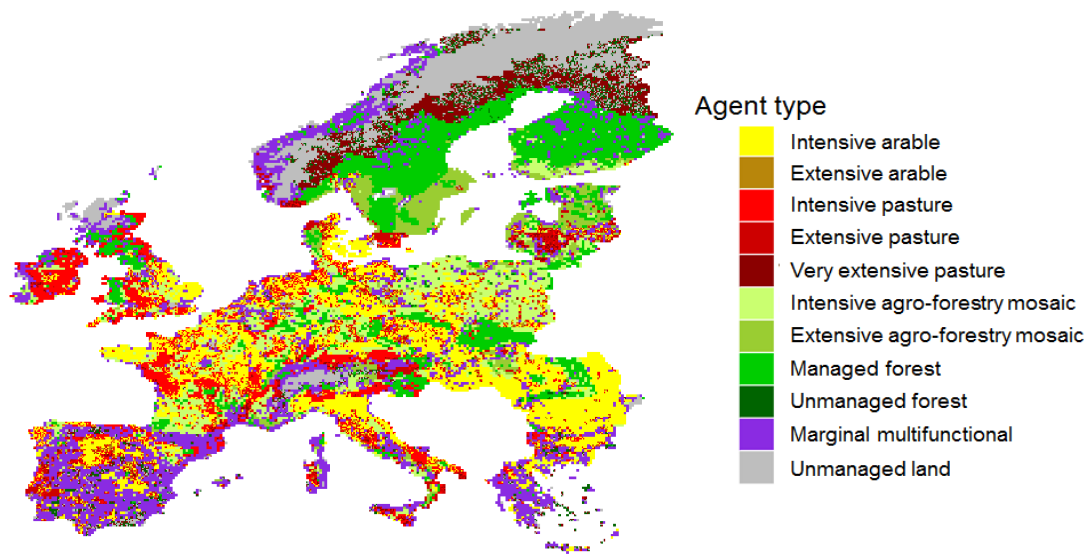


Figure 3.4: Baseline land use map with CRAFTY-EU agent categories (AFTs). Baseline simulations, in which present-day conditions persist indefinitely, produce minimal deviations from this result.

Under the RCPxSSP scenario combinations, CRAFTY-EU simulations produce a range of divergent results. Those most similar to the baseline were produced under RCP2.6 and SSP1, where scenario conditions present few challenges to the production of ecosystem goods and services. Nevertheless, satisfying increasing demands for meat, crops and timber proved difficult, with increasing pressure on the land system. Some previously unmanaged areas were converted to agriculture and forestry, with significant trade-offs in the production of agricultural and forest services, and traditional forms of low-intensity management in marginal areas were projected to decrease in area (Figure 3.5a). Under higher-end climate change (RCP4.5), however, many of these changes were reversed, with unmanaged areas increasing in extent, and intensive agriculture dominating in much of mainland Europe (Figure 3.5b). Substantial areas of intensive agro-forestry mosaic land uses and very extensive pastoral agriculture were projected to be lost from Eastern Europe in particular, with the satisfaction of requirements for goods and services in these regions depending upon production elsewhere in Europe.

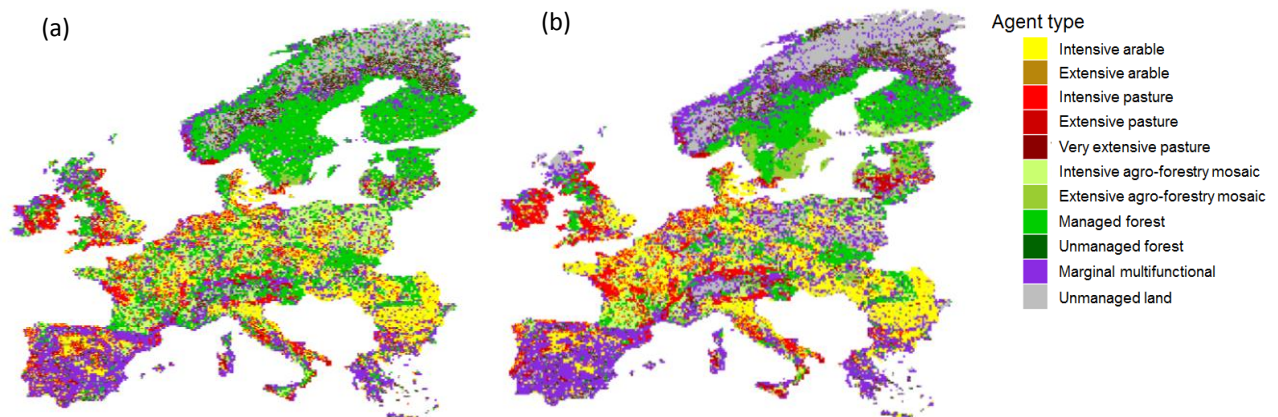


Figure 3.5: Simulated land use maps in 2100 under (a) RCP2.6 x SSP1; and (b) RCP4.5 x SSP1.

Similar changes became more pronounced under more challenging socio-economic scenarios. Changes in land management intensity (Figure 3.6) show trends of de-intensification and abandonment becoming stronger through SSP1, SSP4 and SSP3 under RCP4.5.

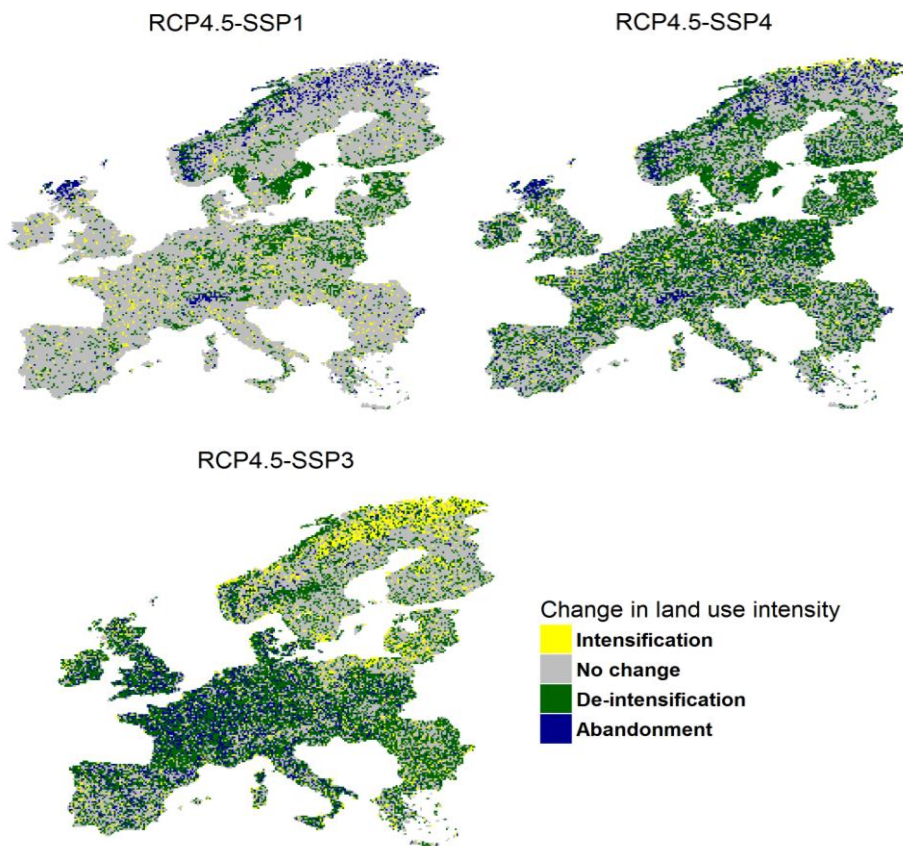


Figure 3.6: Changes in land use intensity in socio-economic scenarios under RCP4.5, relative to RCP2.6 x SSP1. Under SSPs 1 and 4, de-intensification is concentrated in north-eastern Europe, and abandonment in mountainous areas. Under SSP3, however, both processes occur far more widely, with some (attempted) usage of land in the far north being shown as intensification.

Under the most challenging socio-economic scenario (SSP3), de-intensification and abandonment occurs across much of Europe, including in highly productive areas, as a response to dramatic drops in human, financial and manufactured capitals (Figure 3.7). These drops pose particular problems for intensive agriculture, which depends upon a range of inputs (finance, fertiliser, expertise, etc.) and effective distribution networks. As a result, profitability and production levels both decline sharply, eventually causing many simulated land managers to abandon their land, leading to very large shortfalls in supply (Figure 3.7). These shortfalls prompt fragmented, inefficient attempts to produce required goods and services, generating a highly diverse land use system with low levels of productivity and coherence.

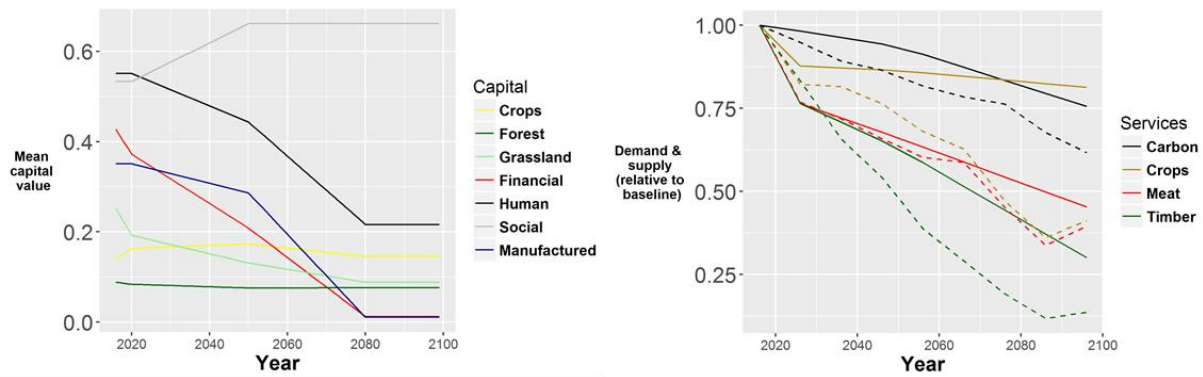


Figure 3.7: Changes in capital values (left) and demand and supply of services (right) under an RCP4.5 x SSP3 combination. In (left), mean capital values across Europe are shown, on a scale of 0-1. In (right), demand is denoted by solid lines and supply by dashed lines.

Simulations under RCP8.5 show that the difficult conditions of SSP3 have unexpected interactions with high-end climate change. Here, rather than mass de-intensification of European land use, climate-driven increases in productivity in some areas allow some intensive agriculture to persist, albeit strongly fragmented and relatively unproductive (Figure 3.8). Supply levels remain well-below demand, but some improvement is projected late in the century, particularly in supplies of meat. In contrast, under SSP5 (which is not simulated under less extreme climate scenarios), climate effects combined with less dysfunctional socio-economic conditions allow demand levels to be met relatively easily. In this case, some areas of land are abandoned as they are surplus to requirements rather than insufficiently productive, although these tend to be concentrated in more marginal areas. The resulting land use projection resembles the baseline in many areas (Figure 3.8).

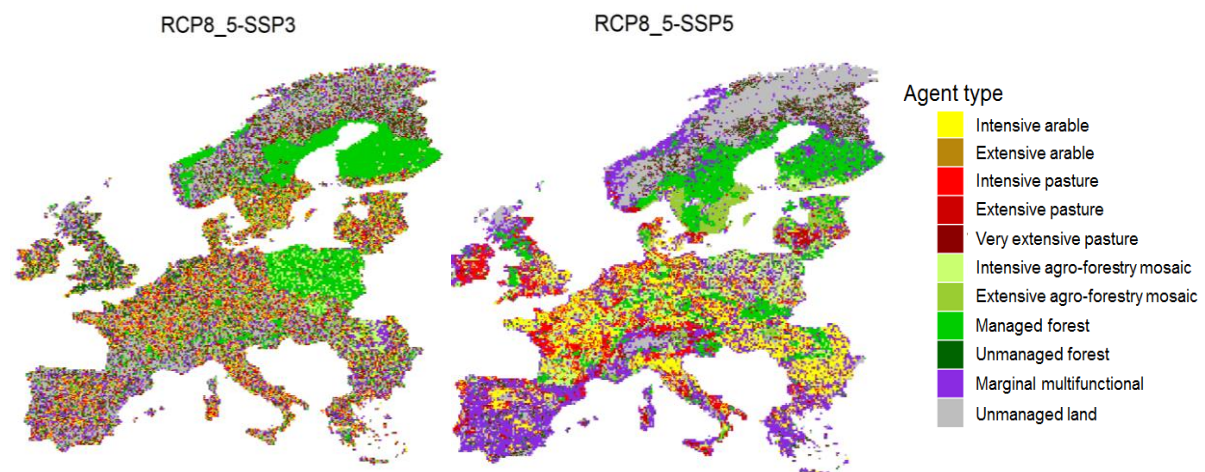


Figure 3.8: Projected land use in 2100 under SSPs 3 and 5, when combined with RCP8.5.

These core results suggest that socio-economic conditions are particularly decisive in future land use patterns, with stronger effects than those of simulated climate change. However, the defined scenario conditions do not include personal and social effects at the level of land manager groups or individuals. CRAFTY-EU is designed to simulate such effects, and was used to combine the above scenarios with behavioural variations affecting land managers' dedication to their land uses, willingness to adopt alternative land uses, connectedness in social networks, sensitivity to institutional interventions, and variable ability to produce ecosystem goods and services. Results of these combined simulations

suggest that the impacts of such behavioural variations depend upon their socio-economic and climatic context, being strongest under more benign scenario conditions (relatively high productivity and stable socio-economic conditions) (Figure 3.9).

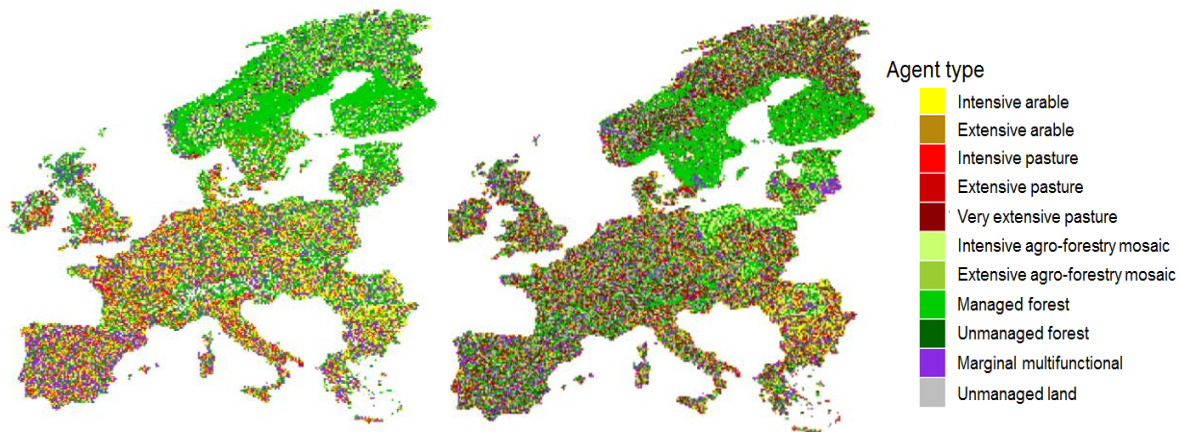


Figure 3.9: Example maps showing effects of behavioural variations between land managing agents under RCP2.6 x SSP1 (left) and RCP4.5 x SSP3 (right). In these simulations, agents' dedication to their land uses (willingness to abandon land) and sensitivity to capital levels for production are subject to small agent-type-specific random variation.

Figure 3.9 shows that under the less extreme conditions of RCP2.6 x SSP1, behavioural variations produce substantially different land use outcomes, increasing the fragmentation of land uses and also the extent of intensive agriculture and forestry. In many marginal area, intensive producers persist for short periods of time if their high levels of dedication or low levels of capital sensitivity (representing cultural or personal preferences, or private capitals that can sustain productivity) allow them to produce temporarily despite low returns. This has the effect of increasing the supply of most goods and services, while decreasing overall productive efficiency. Under RCP4.5 and SSP3, however, the more challenging scenario conditions mean that even relatively large variations in agent characteristics do not produce substantially different outcomes (except at the local scale, where the management of individual cells can vary). A slight increase in intensive management occurs, but supply levels remain static as productive potential is so low. Under simulations with more pronounced behavioural effects, only an almost complete (and highly artificial) insensitivity to capital levels was found to allow agents to produce at levels close to those required under this scenario. Similar trends are found under other forms of variation, and are summarised in Table 3.1.

Table 3.1: Broad effects of behavioural variations simulated by CRAFTY-EU.

Behaviour	Dominant effects
Unwillingness to persist with land uses that offer low returns	Reduces production levels and causes abandonment of some land, especially under challenging socio-economic scenarios. However, increases productive efficiency as agents retreat to most productive land.
Unwillingness to relinquish land to a more competitive agent	Slows rate of change under scenarios, but little effect where de-intensification and abandonment dominate.
Limited ability to search for cells on which to compete	Slows rate of change and can increase fragmentation as efficiency of use decreases

Behaviour	Dominant effects
Limited sensitivity to demand levels	Overall production levels increase and most productive land reliably under use, but production determined by productivity patterns more than by demand; insensitivity to changes in demand levels.
Ability to produce multiple services	Multifunctional producers outcompete single-service (generally intensive) producers where demands or productivity levels are low, but do not perform reliably better under more extreme scenarios.
Institutional interventions	Can successfully alter land use and productivity patterns, especially in less extreme scenarios. However, tends to have unanticipated knock-on effects in other areas, where adjustment occurs in an attempt to satisfy overall demand levels. Realistic interventions unable to counteract extreme scenario conditions.
Social networks	Controls rate of change where social connectedness affects levels of knowledge, uptake of new practices, or willingness to change land use. Have less dramatic effects in extreme scenarios.

3.1.3. European forests under high-end climate change scenarios

Following the approach taken for the IAP2 (see Section 3.1.1), a sensitivity analysis to climatic variations (increase in temperatures up to +11°C and variations in precipitation from -60 to +40%) has been conducted for the forest model ForClim, using maximum volume and/or annual volume increments as indicators of forest productivity (Figure 3.10). Even though results vary depending on the sub-European zone and tree species considered, they highlight the strong sensitivity of forest productivity to these two climatic variables. A decrease in precipitation tends to lead to a dramatic decrease in forest productivity (usually already happening between 0 and -20%), and this effect is aggravated when combined with an increase in temperature. This combined negative impact is stronger in dry areas, typically in Southern Europe, and weaker in cold and wet areas. In Northern Europe and in the Alps, an increase in temperature can even have a positive effect on the growth of species that are currently limited by cold temperatures (for example, Scots pine in the Alps, beech and oak in the Alps and Northern Europe), at least up to certain limits (growth may decrease in the case of extreme warming) and if water is not a limiting factor.

These broad-scale patterns are also observed when using rIAM's Meta-ForClim to project future forest productivity at the European scale. Figure 3.11 presents future maps of forest productivity for Scots pine in 2100, under three different climate change scenarios (low, intermediate and high-end), as well as the difference from the baseline. Results show an increase in forest productivity in Northern Europe and in most mountainous areas, that is, where tree growth is currently limited by cold temperatures and where water will most probably remain non-limiting. Conversely, forest productivity is expected to decrease in Southern Europe and in dry areas of Central and Eastern Europe. In both cases, the amplitude of the positive or negative effects increases with the severity of climate change (i.e. from low to high-end). In Western and Central Europe, the projected variation in forest productivity varies between scenarios and time-periods (see Figure 3.12). More generally, the impact of climate change depends on the degree of warming and water limitation, as a combination of high temperature and abundant precipitation can have a positive effect on forest productivity (cf. Figure 3.10).

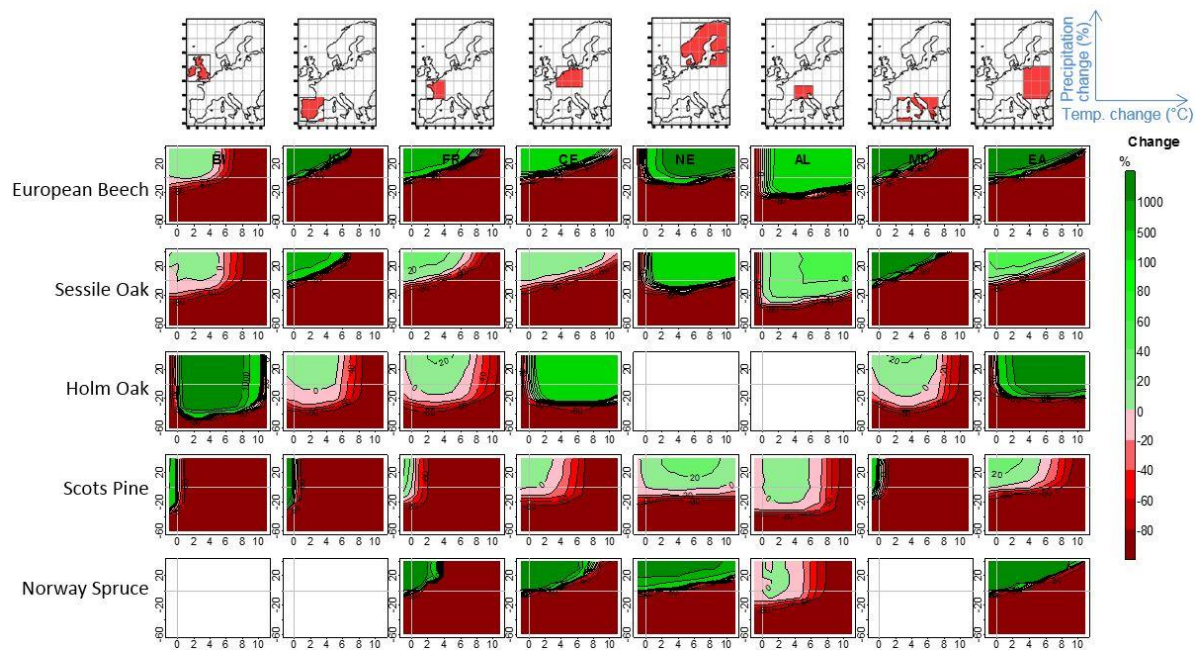


Figure 3.10: Change in forest productivity for Holm oak (as % from baseline value) to variations in temperatures (x axis) and precipitations (y axis) around a representative baseline climate for eight European sub-regions. These Impact Response Surfaces were derived from simulations conducted with ForClim for the grid cell closest to median climatic conditions for each region (i.e. closest to the median values of mean annual temperatures and precipitations sums for the region). The results are shown for a soil with a water holding capacity of 15 cm.

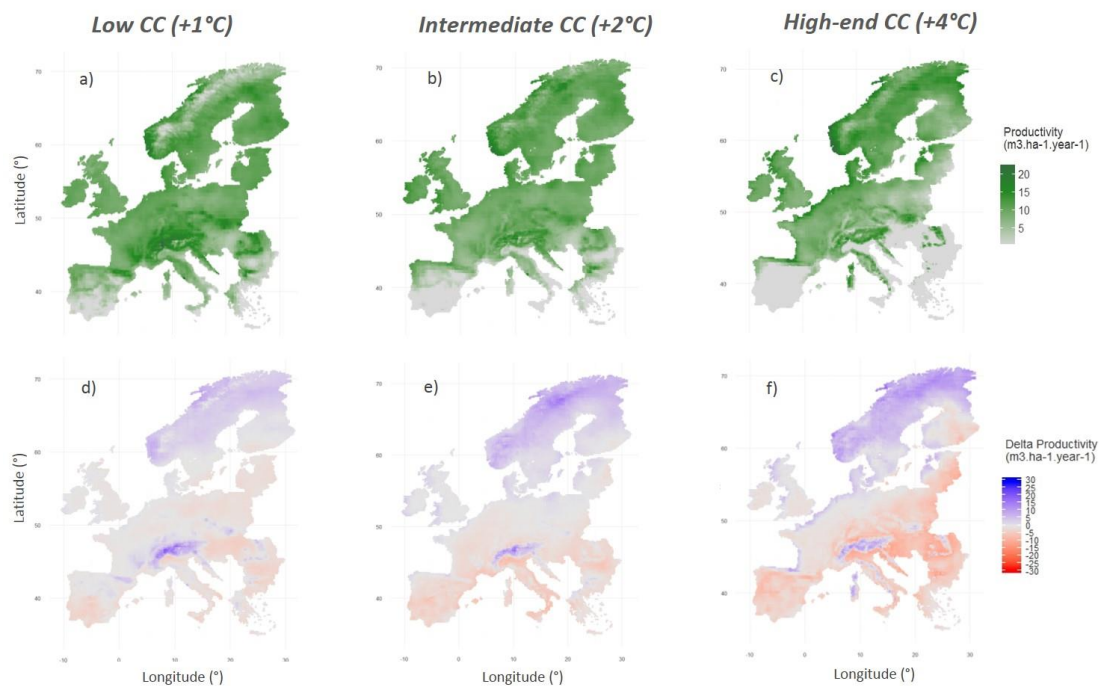


Figure 3.11: Evolution of forest productivity, for Scots pine, under three climatic scenarios. The figure shows the annual volume increment predicted by rIAM's Meta-ForClim for Scots pine in 2100 (upper row, gradient of green) and the difference from baseline conditions (lower row, decrease in red, increase in blue), for three climate change scenarios: a low-end (RCP4.5 GFDL-ESM2M_RCA4; +1°C at the European scale; left), intermediate (RCP4.5 HadGEM2-ES_RCA4; +2°C; middle) and high-end (RCP8.5 HadGEM2-ES_RCA4; +4°C; right). Results are presented for a soil with a water holding capacity of 15 cm.

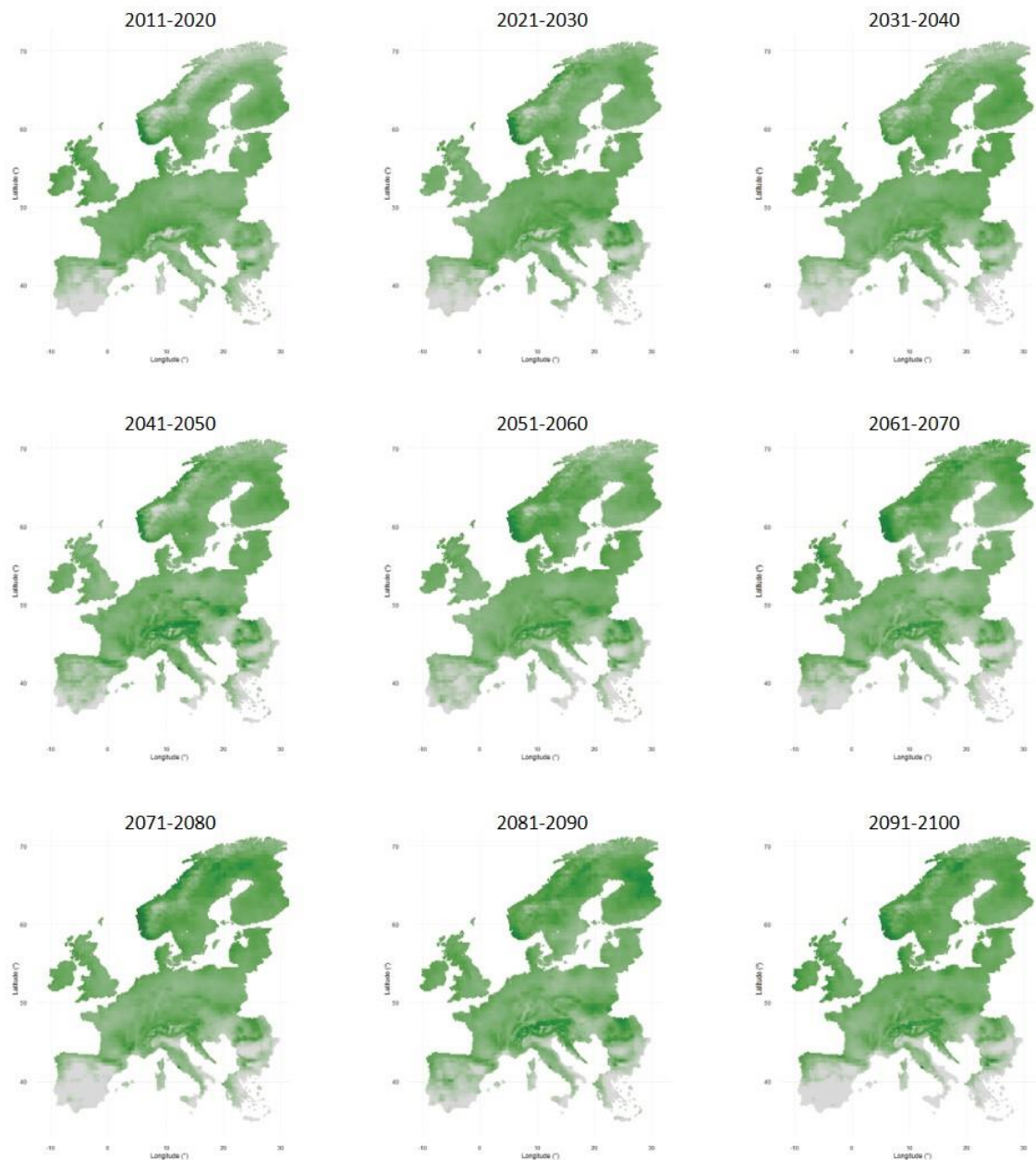


Figure 3.12: Evolution of forest productivity, for Scots pine, over time for a moderate climate change scenario. The figure shows the annual volume increment predicted by Meta-ForClim for Scots pine for nine decadal time steps (from 2011 to 2100) for an intermediate climate change scenario (RCP4.5 HadGEM2-ES_RCA4; +2°C at the European scale). Results are presented for a soil with a water holding capacity of 15 cm.

These trends are generally valid for the forestry sector, but differences exist between species depending on their sensitivity to variations in temperature and precipitation (cf. Figure 3.10) and on their productivity under baseline conditions, especially regarding their current limitation by cold temperatures (high latitudes and elevations) and by drought (Southern Europe). Norway spruce may benefit from an increase in temperatures in Northern Europe and in mountain areas of Central, Western and Eastern Europe (at least when not limited by water); but is expected to be very vulnerable to climate change at low elevations, where it has been introduced out of its natural range for economic

reasons. Oak and beech will also benefit from an increase in temperature at high latitudes and elevations, where they are currently absent or limited by cold temperatures, but may suffer from increased and more frequent droughts, especially in Southern and Eastern Europe. Being a Mediterranean species, Holm oak is more drought tolerant and will be less vulnerable than other species to the projected climate changes. It may even benefit from an increase in temperature and be able to replace other oak and pine species where they become unsuitable. The productivity of Holm oak may, however, be affected under extreme climate change scenarios.

Model predictions should, however, be nuanced and interpreted while considering the multiple sources of uncertainty. First, the comparison of different climatic scenarios (cf. Figure 3.11) reveals a high sensitivity of model predictions to the choice of a given RCP or GCM. The RCP has a clear impact on the degree of warming and thus on temperature-related impacts, with a more pronounced decrease in productivity in Southern, Eastern and Central Europe (at low elevations) under RCP8.5 (Figure 3.11c & f) than under RCP4.5 (Figure 3.11b & e) – here for the same GCM (HadGEM2-ES_RCA4). The increase in productivity is also stronger under RCP8.5 where precipitation is not a limiting factor. Yet, the choice of the GCM also has an impact on the projected climate, both in terms of precipitation and temperature, and thus on the model's predictions. For example, the predictions for RCP4.5 are different for the GCMs GFDL-ESM2M_RCA4 (Figure 3.11a & d) and HadGEM2-ES_RCA4 (Figure 3.11b & e). Warming is lower in the first scenario (+1°C instead of +2°C) and negative impacts are much less pronounced in Western and Southern Europe, while positive impacts can be seen for most mountainous areas. The trend is, however, quite different for Eastern Europe, with more negative impacts under the “low warming” scenario, at least for the time window 2090-2100. This shows that general conclusions should not be derived from a single climate change scenario but should consider the uncertainty related to the choice of the RCP and GCM.

Second, the temporal variability of the climate change scenarios can be important and sometimes of the same order of magnitude as differences between climate change scenarios at a given date. Figure 3.12 shows the temporal evolution of Scots pine productivity under the intermediate climate change scenario (RCP4.5 HadGEM2-ES_RCA4; cf. Figure 3.11). Although the evolution over the different decades is consistent with the general trends highlighted so far, i.e. an overall decrease in productivity in Southern and Eastern Europe and an increase in Northern Europe and high elevation, one can notice that these trends are modulated by decadal variations (Figure 3.12). For example, in Spain, Scots pine productivity is predicted to decrease over time, and is indeed much lower in 2091-2100, but is yet projected to increase temporarily around 2050 and in 2081-2090. The difference in productivity between 2081-2090 and 2091-2100 appears then to be as important as the difference between the two GCM scenarios for RCP4.5 in 2100 (Figure 3.11). Although no systematic analysis of the impact of these two sources of uncertainty has been conducted so far, this highlights the fact that results should be analysed and discussed while considering both aggregated and detailed results across spatial and temporal scales. It also raises the question of the impact of decadal variability in the simulations conducted with the rIAM. In the case of forest productivity, these important variations may have repercussion on the allocation of forest area by the land allocation model and on the choice of the tree species to (re-)plant.

Finally, the uncertainty relative to the forest model itself should also be taken into account. Justified by the necessity to have a simpler and faster model to be implemented on the rIAM platform, the development and use of a simplified version (meta-model) of ForClim (Meta-ForClim) to project the evolution of forest productivity under climate change across Europe may introduce an additional source of uncertainty in the predictions. The comparison of the productivity predicted by the two models for the set of tree species (see Section 5 on Discussion) revealed that, although some slight discrepancies could be detected, Meta-ForClim's predictions are overall consistent with ForClim and

the general spatio-temporal patterns are respected. Using Meta-ForClim instead of ForClim in the rIAM should therefore have rather limited impact on projections.

On the contrary, using different forest models in the IAP2 and rIAM platforms might have non-negligible impacts on the predictions made for the forestry sector and, by extension, on the predicted evolution of land uses over time and under different climate change scenarios. Meta-Gotilwa (IAP2) and Meta-ForClim (rIAM) are two conceptually and technically very different models relying on different assumptions, especially regarding the consideration of CO₂ fertilisation. Meta-Gotilwa is a process-based model in which photosynthesis is simulated explicitly and drives forest productivity, with a positive effect of CO₂ fertilisation (i.e. increased atmospheric CO₂) on tree productivity. Conversely, ForClim, is a gap model that relies on rather simple assumptions and does not explicitly simulate the photosynthesis process, nor the impact of increased atmospheric CO₂. In addition, the species represented in the two models differ regarding their current distribution, their sensitivity to drought and to projected climate changes. Gotilwa has been designed for Mediterranean forests, while Meta-ForClim was initially developed for Central Europe. As a result, Meta-Gotilwa considered species present in Southern Europe (Aleppo pine, Maritime pine, Scots pine, European beech, Holm oak), which are therefore more drought-resistant and generally less sensitive to climate change than the set of species chosen to cover the entirety of Europe in Meta-ForClim (Norway spruce, Sessile oak, Scots pine, European beech, Holm oak). Although the last three species (out of five) were common in the two models, their calibration for Mediterranean forests in Meta-Gotilwa might indirectly consider local adaptation to drier conditions and thus make them more drought resistant than in the default calibration of meta-ForClim. Altogether, this leads Gotilwa to predict mostly positive impacts of climate change on tree productivity, even in the Mediterranean region (Sabaté et al. 2002), due to the positive impact of CO₂ fertilisation that counteracts the negative impacts of increased temperatures (especially if water does not become too limiting). In IAP2 runs, this general increase in forest productivity under climate change makes it easier to meet the timber demand and thus results in a decrease of the forest area in Europe (see Section 3.1.1). With Meta-ForClim, the productivity gain will be mostly limited to Northern Europe and mountain areas, while productivity loss is anticipated in many areas, requiring a switch to more drought-adapted species when possible. This will modify the land allocation results in the rIAM compared to the IAP2, which will need to be taken into consideration when comparing simulation outputs from the two platforms.

3.1.4. Trends in urbanisation under varying socio-economic scenarios

The remainder of this section explores future urbanisation trends within Europe under the European Shared Socioeconomic Pathways (SSPs). It should be noted that urban modelling is independent of climate (RCPs).

Spatial variability in artificial surface expansion across Europe

The extent and spatial pattern of future artificial surface expansion is highly dependent upon the socio-economic scenario considered (Figure 3.13); artificial surface extent varies from 4% (SSP1, SSP4) to 9% (SSP5) of the European land area by 2100.

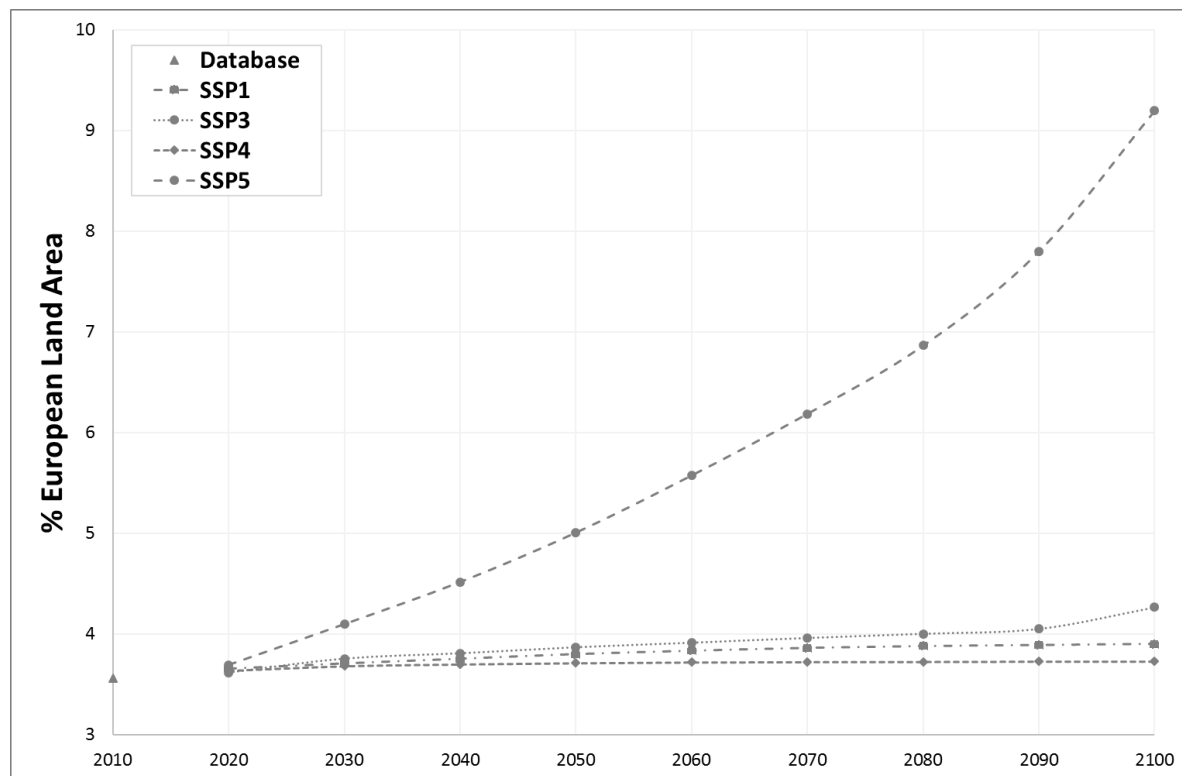


Figure 3.13: The total extent (as a percent of European land area) of artificial surfaces estimated across Europe under four different socio-economic scenarios (SSPs).

At a European scale, SSP5 is characterised by urban sprawl; artificial areas expand (from ~4%) to over 9% of the European land area by 2100. This sprawl parallels the scenario storyline in which a growing, individualistic and wealthy society seek larger properties in suburban and rural areas. Urban sprawl of this magnitude will (i) increase the competition for land (for example, for food production or nature protection), and (ii) detrimentally impact ecosystem services and biodiversity. The Cities of Tomorrow report states that “*urban sprawl and the spread of low-density settlements is one of the main threats to sustainable territorial development*” (EU, 2011).

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

At a sub-European scale, a clear distinction exists in the modelling outcomes of selected Eastern European countries (Bulgaria, Croatia, Lithuania, Latvia and Romania) and the rest of Europe (Figure 3.14); a distinction driven by demographics. These Eastern European countries are, within SSP5, characterised by an aging, but overall decreasing population (IIASA, 2015); a distinct contrast to the population increases associated with SSP5 in the remainder of Europe. Consequently, minimal artificial surface expansion is predicted in the specified Eastern European countries under SSP5. In this region, artificial surfaces increase is most substantial in SSP3. While this scenario is also characterised by an aging and declining population, a slow rate of change combined with a shift towards suburban development (associated with urban in-migration and weak planning laws) results in artificial surface expansion.

The SSPs highlight the potential extent of future artificial surface change under very different socio-economic circumstances. Important distinctions between the scenarios include (i) the potential to mitigate artificial surface expansion via increasing population densities (as evident in SSP1), (ii) the potential of artificial surfaces to 'sprawl' in the presence of increasing populations, and/or changing residential preferences (SSP5), (iii) the influence of changing residential habits which do not guarantee a static artificial surface footprint when populations decline (selection of countries in SSP3), and (iv) regional variability in artificial surface expansion.

The influence of land use planning and residential preferences on future urbanisation

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

European scale statistics mask underlying variability, as exemplified for the suburban residential type (Figure 3.15), driven by (i) regionally variable demographics and/or residential preferences, and (ii) a strong correlation between new developments and the existing artificial surface network. Cities, and their associated suburbs, within Belgium, the Netherlands, western Germany and southern United Kingdom, are characterised by their close proximity. Future suburban developments are typically focused in these densely populated regions; highlighted by the concentrated artificial surface change (darker colours) of Figure 3.15. By contrast, Denmark, Sweden, Finland, France and the interior of Spain and Portugal are characterised by more sparsely distributed cities. Suburban expansion (Figure 3.15) tends therefore to be associated with 'hotspots' of change around existing cities. These regional differences highlight contrasting sustainable development challenges.

Urban, suburban and rural populations under future socio-economic scenarios

Population projections predict, at a European scale, an overall increase in population in the SSP1 and SSP5 scenarios. Conversely, SSP3 and SSP4 are characterised by declining (and aging) populations (IIASA, 2015). Modelling the SSP storylines for this overall demographic change, and link between life-cycle stage and residential preferences, allows RUG to explore the residential circumstances of this future population (Figure 3.16).

At the European scale, the increasing population projected in SSP1 predominantly resides in cities, which account for a higher proportion of the total population (44%) when compared to the baseline (36%), (Figure 3.16b). An increasingly city dwelling population is evident in SSP4 where cities become the predominant residential type, housing 53% of the population (Figure 3.16b). The largest change in the residential structure of the population, at a European scale, is observed in the urban sprawl of SSP5; a substantial decrease in the proportion of the population resident in cities (declining to 18%) and increasingly suburban (36%) /rural (46%) population (Figure 3.16b).

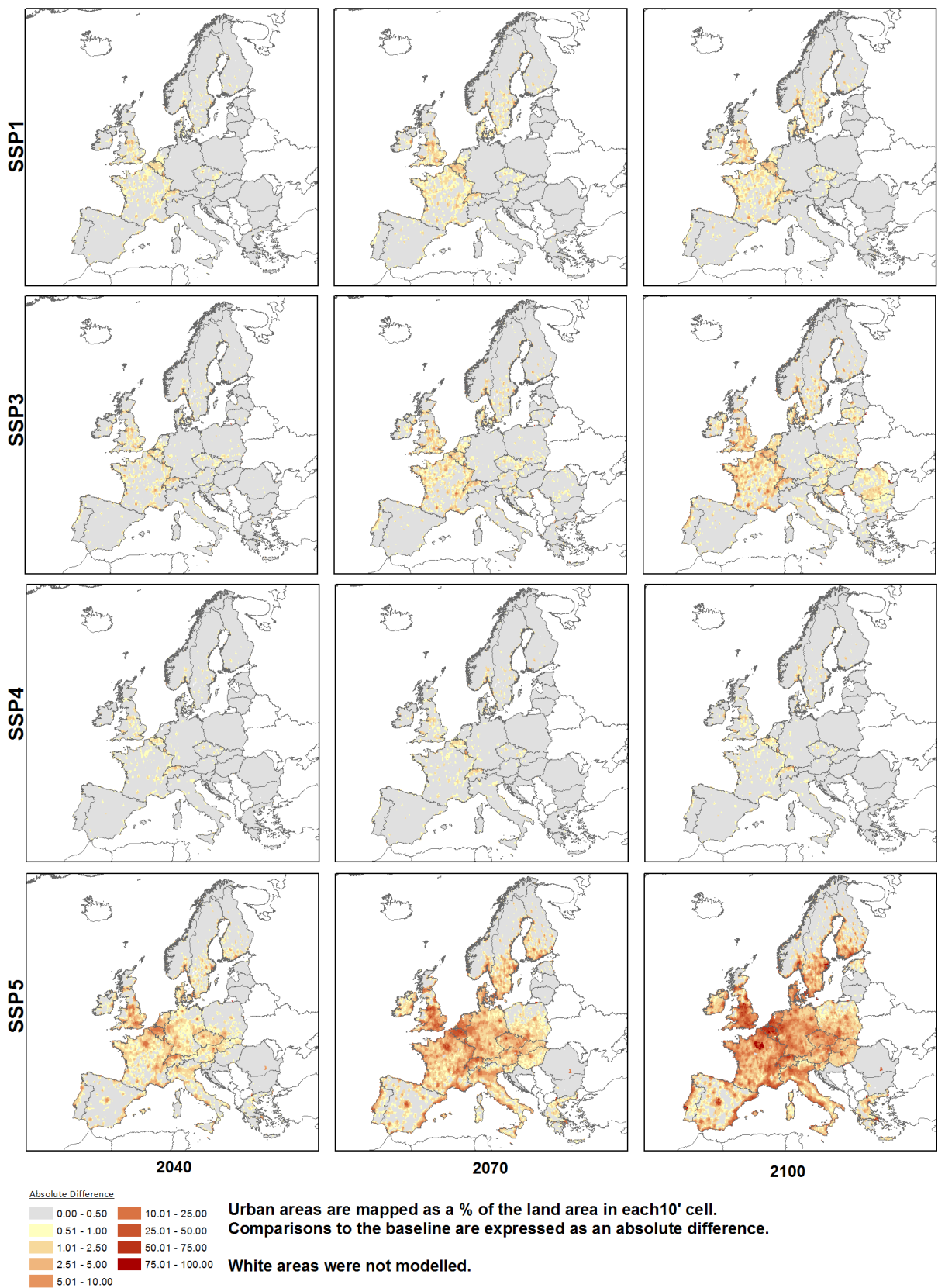


Figure 3.14: The predicted change, from baseline, in artificial surface extent by 2100 under four different socio-economic scenarios. Darker colours are associated with greater artificial surface expansion. Change is expressed as the absolute difference in artificial surface extent.

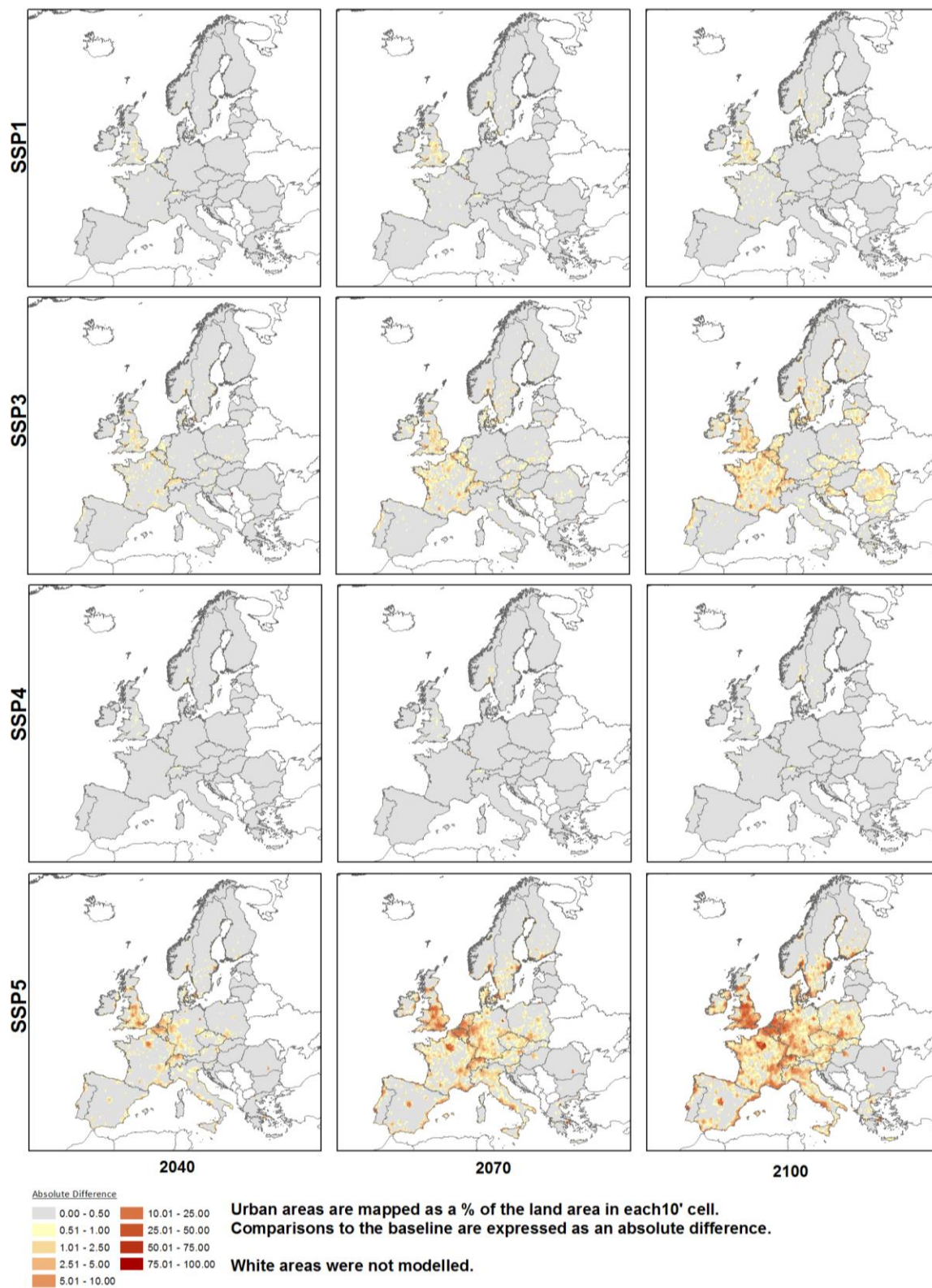


Figure 3.15: The predicted change, from baseline, in suburban areas by 2100 under four different socio-economic scenarios. Darker colours are associated with greater artificial surface expansion. Change is expressed as the absolute difference in artificial surface extent.

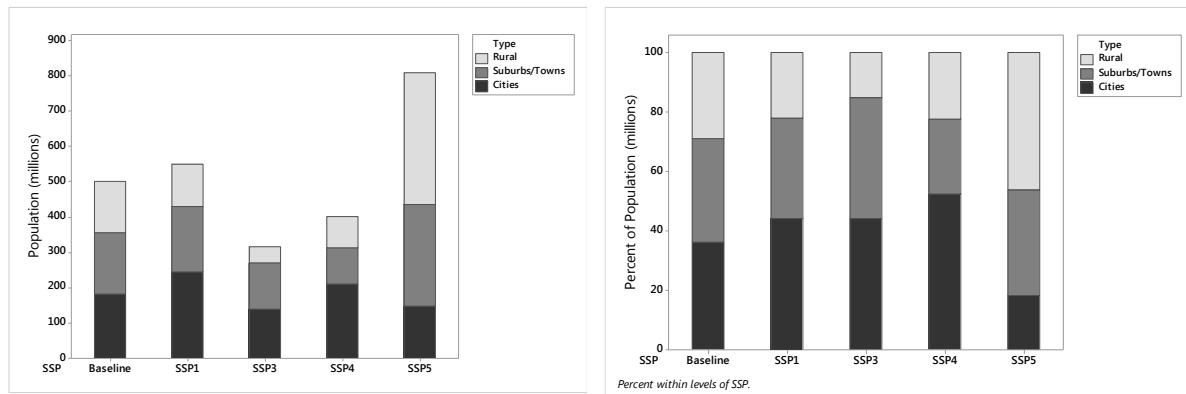


Figure 3.16: European scale population as a function of residential type at 2100 under four socio-economic scenarios; (a) Population count (Millions), and (b) proportional representation.

Residential types are a key indicator of access to social infrastructure such as education, health care, and broadband. A shift towards the higher density urban areas in SSP1, and to some extent SSP3 and SSP4, is advantageous in terms of ensuring service provision and transport efficiencies. However, these advantages are unlikely to be realised in the socio-economic circumstances of SSP3 and SSP4. The dense cities and urban ghettos of SSP4 highlight regions where social issues are typically prevalent (unemployment, poverty, segregation, exclusion, crime, etc.) and urban regeneration policies should be targeted. The urban sprawl of SSP5 does not promote efficiencies in the provision of public services; a shift to suburban/rural based populations is indicative of distributed service provision. This poses key environmental challenges in regard to, for example, achieving emission reduction targets given the foreseen use of cars rather than low-carbon public transport.

Comparing the urban model within IAP2 and rIAM

Future urbanisation within Europe, while showing broadly similar trends, does vary as a consequence of the modelling approach. Variability can be observed between the IMPRESSIONS IAP2 (Figure 3.2) and results described above for RUG which has been further developed for rIAM (Figure 3.13). These differences reflect both model uncertainty and the complexity of the modelling approach implemented.

Within the IAP2, the extent of urban development is controlled, primarily, by changes in the population, and wealth of this population (as indicated by GDP). An increasing population implies an increasing artificial surface extent, that is additional housing is required to home the population. With increasing wealth, urban densities are assumed to decline (houses become largely and more widely spread). This urban sprawl is, to some extent, controlled by a planning variable which defines whether regulations enforce compact (versus sprawling) urban forms. All relationships between these variables are based on historic trends urbanisation trends.

The explicit inclusion of age-groups and residential types within the modelling approach afford RUG additional mechanisms with which to control future urbanisation trends. Changes in the demographic profile of the population now define the types of housing (residential types) in demand. Each residential type has a different (and changing) set of spatial characteristics (or building densities). Society can now change their residential preferences; as a function of the socio-economic conditions. By adding this model complexity, RUG is able to encompass more of the urban storyline elements outlined within the SSPs.

Differences between the urban modelling from IAP2 and rIAM within each of the socio-economic scenarios are therefore a consequence of:

- **European SSP1** – While new developments are defined to be spatially compact, an increasing population and societal wealth drive urban expansion within the IAP2. Within rIAM, this increasing population is also acknowledged. However, an additional element of the storyline, which states that an environmentally friendly society seek compact, city-centre dwellings can be better encompassed within the model parameterisation. The population are defined as moving towards (preferring) the city-centre residential type. Furthermore, the residential density of city-centres can be increased to replicate high-rise dwellings. This more nuanced approach to model parameterisation limits the required urban development within rIAM (and gives contrasting results to the IAP2).
- **European SSP3** – A declining population, within this scenario, limits artificial surface expansion within both the IAP2 and rIAM. A slightly increased rate of artificial surface expansion is observed within rIAM as a consequence of rural abandonment and a shift, by the population, towards the urban fringes (suburban areas) under weak planning laws. This rural abandonment is not explicitly handled within the IAP2. However, modelled outcomes are similar.
- **European SSP4** – While the population initially increases, this scenario is characterised by an overall declining population trend. Artificial surface expansion, within the IAP2, is therefore more closely linked to the increasing GDP projected for the scenario. Urban modelling in rIAM is not explicitly linked to changes in GDP. As a consequence, a declining (and increasingly urbanised) population is not associated with significant artificial surface change. Within rIAM, changes in GDP are still modelled. However, they are associated with manufacturing capitals and the social elite (typically located in the more expansive residential types). This differing treatment of GDP by the modelling approaches leads to greater uncertainty (and differences) in the rIAM versus IAP2 projected outcomes.
- **European SSP5** – Both the IAP2 and rIAM project increasing urbanisation within this scenario. This reflects the scenario storyline that an increasing, and increasingly wealthy population seek larger properties. rIAM is characterised by a more gradual and slightly increased rate of artificial surface sprawl (by 2100). This difference is a consequence of rIAM encompassing both multiple residential types and decadal time-stepped modelling. With these updates, it is possible, for rIAM, to shift societal preferences more gradually to expansive suburban and rural areas. This detailed treatment of the different residential types, and their spatial characteristics, will magnify the urban sprawl already projected by the IAP2.

From this comparison, it is evident that the more detailed treatment of populations (handled as age-groups with different residential preferences), residential types (each with differing spatial characteristics) and the introduction of additional urbanisation drivers (changing societal preferences) influence model outcomes; projected urbanisation trends. Increased model complexity is beneficial in terms of providing a more detailed representation of urbanisation processes. However, increasing model complexity must be balanced with the need to accurately define, parameterise and quantify these processes. Initial testing indicates that the more nuanced outputs of rIAM are compatible with the storylines of the SSPs.

3.2. Water resources, high river flows and water use

3.2.1. Climate change impacts on hydrology using SWIM

Danube

Projected changes in discharge under the RCP4.5 and RCP8.5 climate scenarios are shown in Figure . The projected changes in climate lead to a slight increase in discharge in the beginning of the year (January, February) under both climate projections. This increase is more pronounced towards the end of the century. The relative changes are more than two times higher under the RCP8.5 compared to RCP4.5. At the same time, throughout the rest of year the flow is projected to decrease by on average up to -10 to -15%, as indicated by the multi-model mean. The projected trends indicate shifts in seasonality of the Danube river flow, i.e. the spring peak associated with snowmelt would appear earlier due to higher temperatures. Similar results were also reported by Stagl and Hattermann (2015).

In the case of the RCP8.5 scenario, simulations driven by one climate model – HadGEM2-ES project a strong increase in flow throughout the year (except in early spring) in the mid- and end-century, in the contrast to other models, which tend to agree on the decreasing trends in late spring, summer, autumn and the beginning of winter.

Northern Dvina

The seasonality of discharge of the Northern Dvina River is projected to be altered under both climate projections (Figure 3.18). All model results agree that the spring peak will be shifted to an earlier period: from May-June in the reference period to March-April in all future periods. This shift becomes more pronounced over time, reaching a discharge that is up to 4 times higher in March-April under RCP8.5, and up to two times higher under RCP4.5. Additionally, the model simulations show a slight increase in the late autumn and early winter discharge. Such shifts maybe due to an earlier snowmelt caused by increased temperature, as could also be the case for the Danube River.

It should be noted that the Northern Dvina catchment lies outside the EU CORDEX domain; therefore the combined GCM-RCM climatic scenarios used for other catchments could not be used in this case. The climatic datasets for this basin were obtained directly from the GCM simulations, and then bias-corrected and downscaled to the WATCH grid dataset.

Emon

The discharge of the Emon River is projected to increase in winter and summer under the RCP4.5 scenario until the end of the century. However, at the end of the century discharge is projected to decrease throughout the year, apart from in the late winter-early spring period when an increase in discharge is projected (Figure). Under the RCP8.5 scenario, an increase in discharge throughout the year is simulated apart from a slight decrease in April and May for the mid and far future time slices. In general, an overall increasing trend for discharge of the Emon River was found.

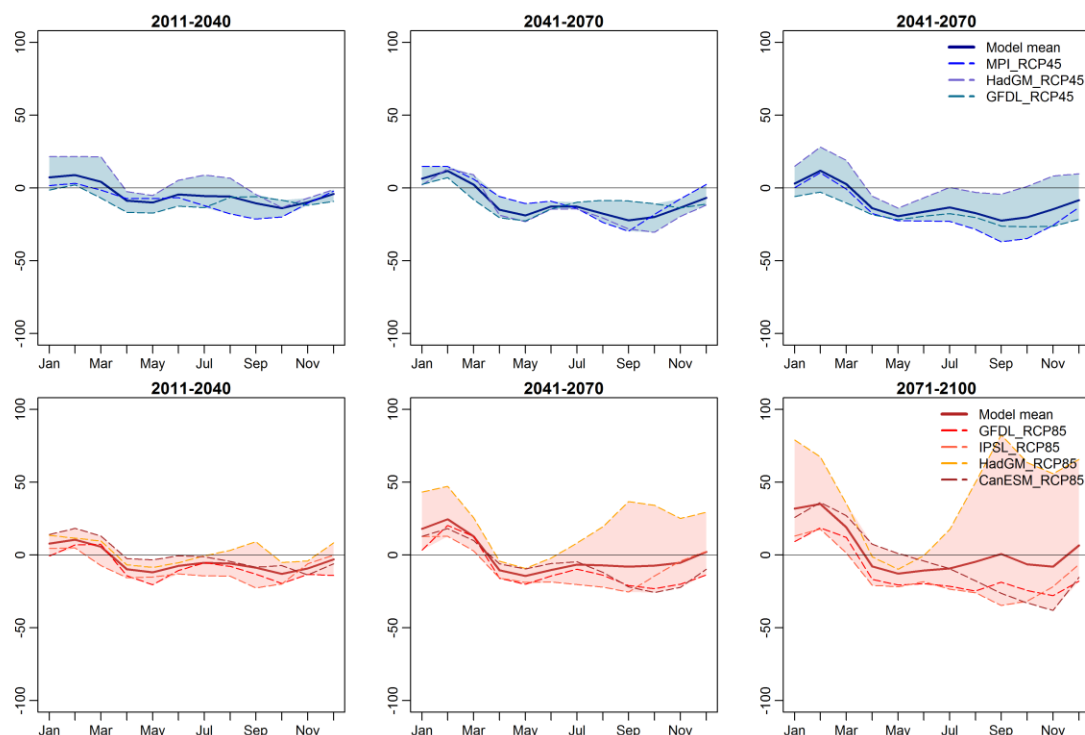


Figure 3.17: Changes (in % from baseline) in discharge at the Danube River outlet (Ceatal Izmail) with respect to the reference period for three time slices, driven by the GCM-RCM climate projections under RCP4.5 (upper row) and RCP8.5 (lower row).

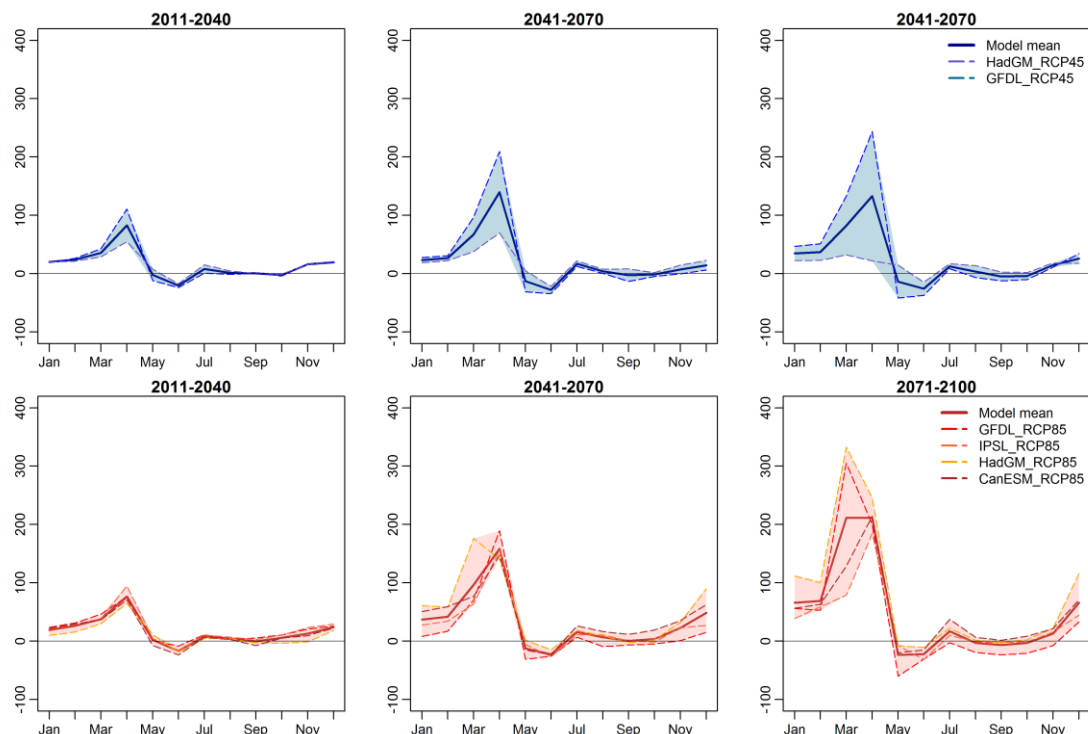


Figure 3.18: Changes (in % from baseline) in discharge at the Dvina River outlet (Ust-Pinega station) with respect to the reference period for three time slices, driven by the GCM-RCM climate projections under RCP4.5 (upper row) and RCP8.5 (lower row).

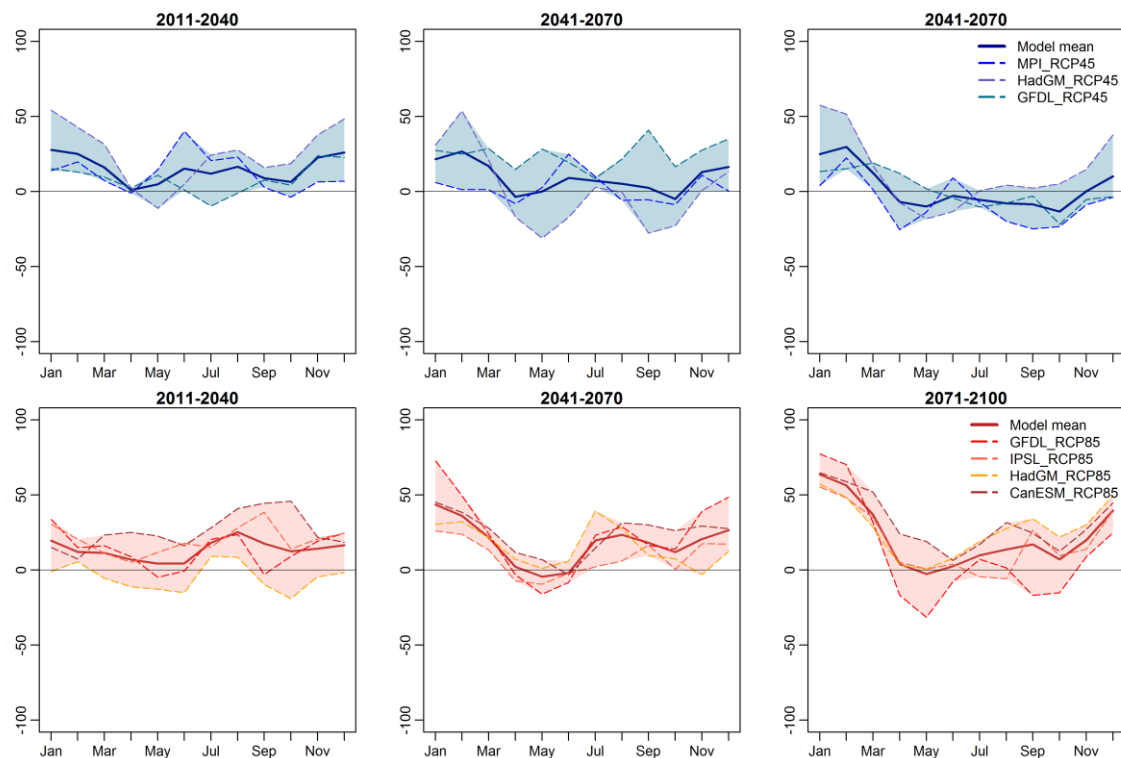


Figure 3.19: Changes (in % from baseline) in discharge at the Emon River outlet (Cetae - Izmael) with respect to the reference period for three time slices, driven by the GCM-RCM climate projections under RCP4.5 (upper row) and RCP8.5 (lower row).

Lule

The discharge of the Lule River is projected to increase throughout the year under both RCP scenarios (Figure). All model outputs agree on this trend. The strong increase in April-May (up to two times under RCP8.5) indicates a probable shift in seasonality of the Lule River, where the peak associated with snowmelt will appear earlier.

Rhine

The simulations for the Rhine River show a potential increase in discharge throughout the year under both climate scenarios for the near future period (Figure 3.21). Further into the future (mid- and end-century), this increasing tendency is only seen in December and the first five months of the year, whilst flow is projected to slightly decrease in summer and early autumn months under RCP4.5. Similarly, under the RCP8.5 projection, a slight decrease is projected in early autumn for the far future period.

Tay

The discharge of the Tay River is projected to increase slightly in the nearest future period, with a maximum of +20% in summer months under both RCPs (Figure 3.22). In the intermediate and far future time slices, the flow is expected to increase in the first half of the year, and decrease in late summer and early autumn months under both RCPs.

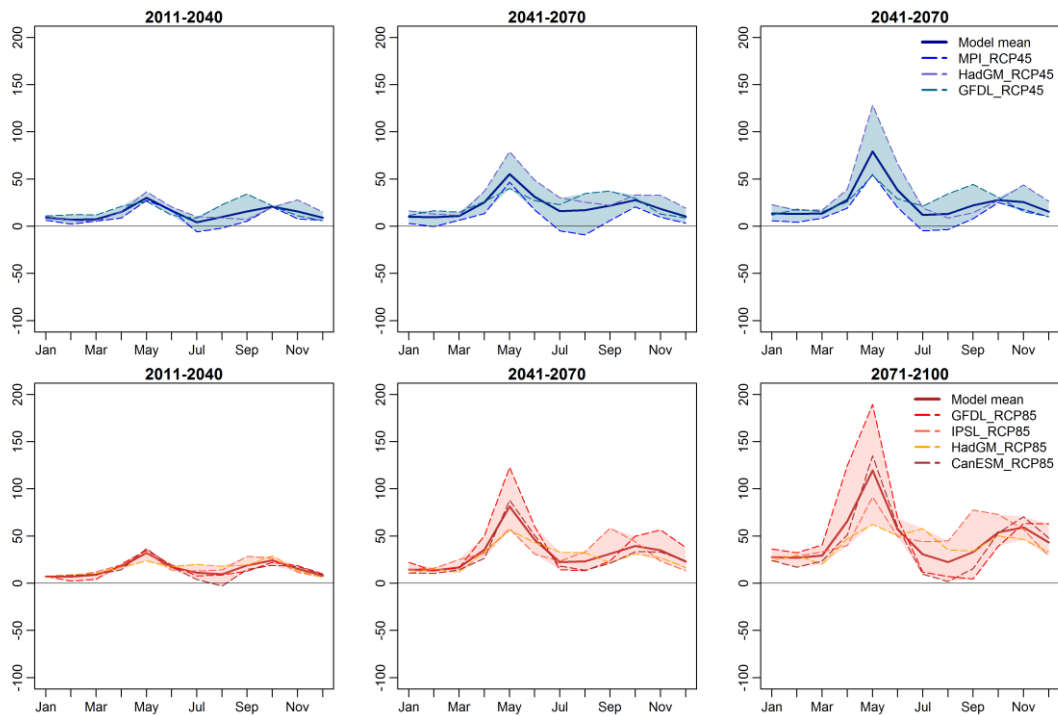


Figure 3.20: Changes (in % from baseline) in discharge at the Lule River outlet (at the Stora Luleälven reservoir outlet) with respect to the reference period for three time slices, driven by the GCM-RCM climate projections under RCP4.5 (upper row) and RCP8.5 (lower row).

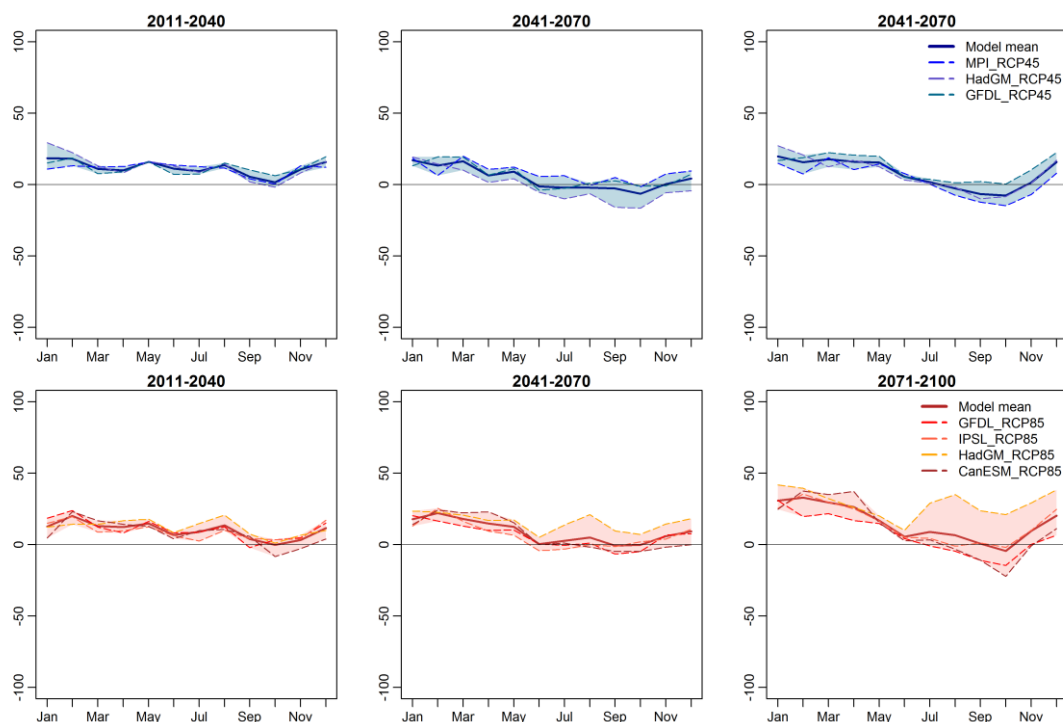


Figure 3.21: Changes (in % from baseline) in discharge at the Rhine River outlet with respect to the reference period for three time slices, driven by the GCM-RCM climate projections under RCP4.5 (upper row) and RCP8.5 (lower row).

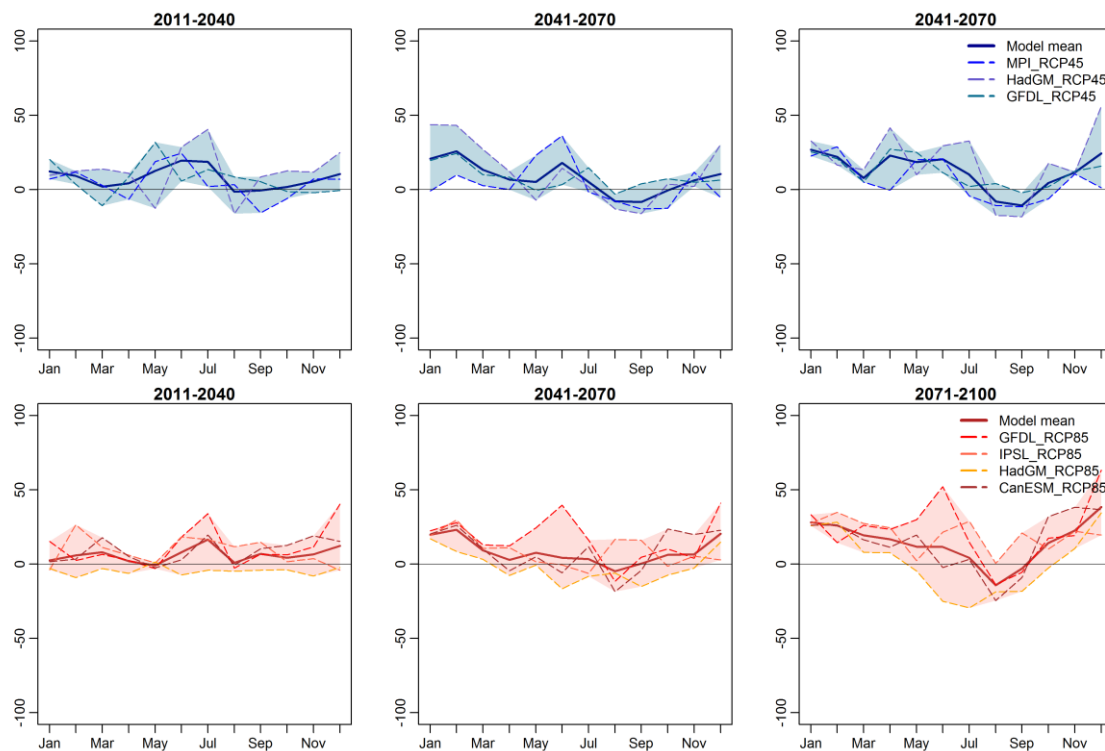


Figure 3.22: Changes (in % from baseline) in discharge at the Tay River outlet (Ballathie) with respect to the reference period for three time slices, driven by the GCM-RCM climate projections under RCP4.5 (upper row) and RCP8.5 (lower row).

Tagus

The overall discharge of the Tagus River is projected to decrease throughout the year at the mid- and end of the century under both RCPs (Figure). The degree of change is more pronounced under RCP8.5, and reaches up to -50% lower discharge throughout the year under RCP8.5, and up to -25% under RCP4.5. In the mid-century the flow is projected to decrease by 30% under RCP8.5, and by 10-20% under RCP4.5. It is notable that the simulations driven by the HadGM model, in contrast to the simulations driven by the GFDL and MPI models, project an increase in the flow of the Tagus River in the mid-century under the RCP4.5 climate scenario.

Summary of key findings

The hydrological impacts of projected climate change across selected European river basins using SWIM are very heterogeneous as indicated by the multi-model means of the ensembles of projections used. The dynamics of the projected changes were similar under both the RCP4.5 and RCP8.5 climate change scenarios applied, although under the RCP8.5 the magnitude of projected changes was more pronounced reaching its' maximum by the end of the century. The trends for these changes can be considered to be robust, as the majority of the models agree on the direction of changes. However, there is important climate model uncertainty as the HadGEM2-ES model under the RCP8.5 scenario led to projected changes in hydrological behaviour that were in a different direction in some basins to that from the other climate models.

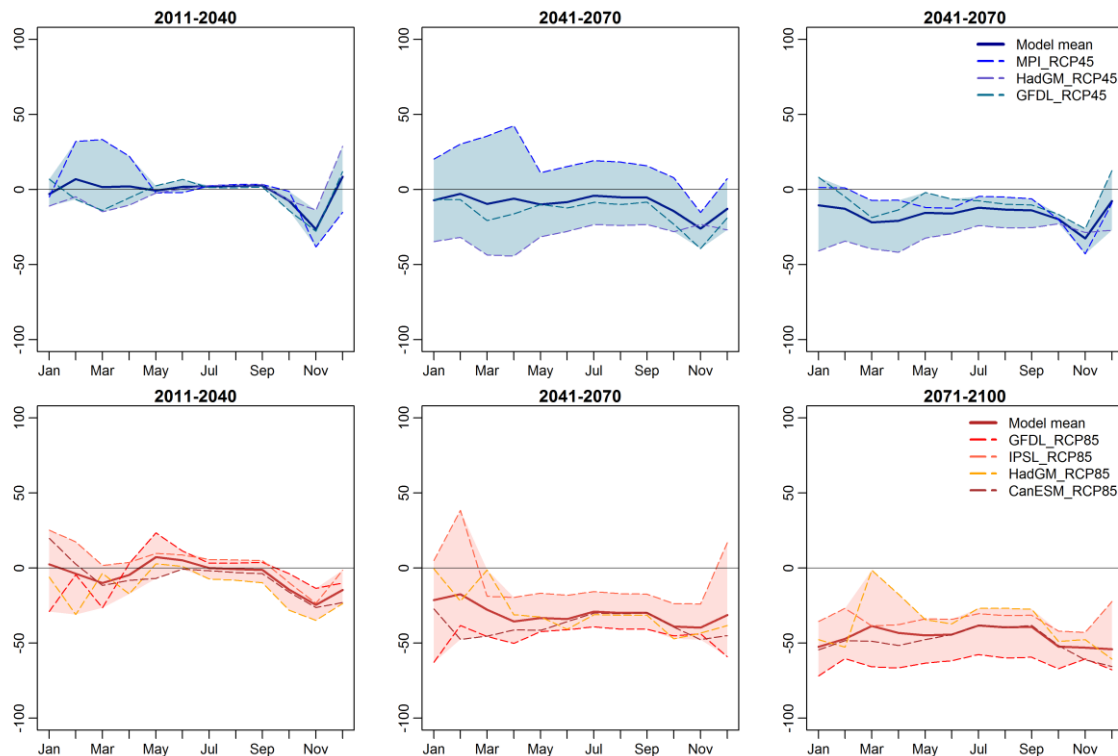


Figure 3.23: Changes (in % from baseline) in discharge at the Tagus River outlet (Almourol station) with respect to the reference period for three time slices, driven by the GCM-RCM climate projections under RCP4.5 (upper row) and RCP8.5 (lower row).

In general, the SWIM simulations show strong changes in seasonality of discharges for Northern Europe. The spring peak discharge of the northern basins (especially in the far North) is expected to be earlier and higher than in the reference period. The low flow periods are also expected to shift in time. In general, in Northern Europe and Scandinavia water availability is projected to increase in total, especially in winter and early spring months. In Central and Eastern Europe (Danube) slight increases in winter discharge and decreases throughout the rest of the year were simulated, whereas in Central and Western Europe (Rhine) increases in the winter months and very slight decreases in the summer during the low flow periods were found. In the Southern Europe (Tagus) the water resources availability is projected to decrease strongly throughout the year. However, it must be recognised that there is considerable heterogeneity in catchment response that is not captured by the limited number of catchment simulated.

3.2.2. Climate change impacts on high flows using SWIM

The SWIM model has been used to simulate the number of high flow days per year; this is defined as the daily flow with a 5th percentile probability of exceedance (i.e. a flow that is only exceeded 5% of the time) over the entire simulation period 1981-2100 (Figure 3.24). Three broad patterns of response in multi-model mean under the RCP4.5 projection can be seen:

- In the Emon, Lule, Rhine and Tay, the number of the high flow events per year is projected to increase with time under both the RCP4.5 and RCP8.5 scenarios, with the increase being greater in the RCP8.5 scenario.
- In the Danube, the number of high flow events in the multi-model mean shows a decreasing trend under the RCP4.5 scenario, but a strong increase under RCP8.5 (although this latter

result arises from the hydrological results using the HadGEM2-ES model which projects a very strong increase in flows, in disagreement with the rest of simulations).

- In Northern Dvina, the number of high flow events show no trend under the RCP4.5 scenario, and only a slight increase under the RCP8.5 scenario (although the SWIM model of the Northern Dvina River was under-representing high flows during the calibration – validation phase of the modelling).
- In the Tagus, the number of high flow events per year is projected to decrease slightly under the RCP4.5 scenario and significantly under RCP8.5, with up to a five-fold reduction by the end of the century.

3.2.3. Impacts and vulnerability related to water stress – modelling results from WGMM

As the most severe water stress was projected at the end of the century in the majority of the scenarios, the results focus mainly on the 2080s (2070-2100). In addition, it is shown how impacts/vulnerability evolve over time for selected examples. To make comparison across scenarios easier, results are also presented in terms of spatially aggregated indicators. The aggregation is done for the four European regions “Northern Europe”, “Southern Europe”, “Western Europe”, and “Eastern Europe” to cover the heterogeneity of climate change across Europe (Figure).



Figure 3.25: European regions aligned with the borders of "river basins" used in WGMM.

The simulated change in annual water availability in European river basins due to climate change by the 2080s as compared to the baseline (1981-2000) is shown in Figure 3.1 for RCP2.6, RCP4.5 and RCP8.5 (based on the default climate model). For RCP2.6 little change was observed except a moderate increase in water availability in Eastern Europe. In Northern, Southern and Western Europe the default climate model represents the dry extreme within the ensemble (Figure 3.2) while it represents the wet extreme in Eastern Europe. However, as the ensemble variance is rather low for RCP2.6 results for other climate models are within a range of $\pm 10\%$ regionally.

Water availability increases by up to 50% in Northern and Eastern Europe for RCP4.5, while it decreases by 10 to 50% in Southern Europe. The results for the default climate model (HadGEM2-ES_RCA4) represent the ensemble median in Northern and Western Europe and the wet extreme of the ensemble in Southern and Eastern Europe (Figure 3.2). On a regional bases, the dry extreme for RCP4.5 leads to an additional reduction of water availability by about 15% in Southern Europe and a slight reduction (-5%) in Eastern Europe.

Figure 3.24: Number of high flow days in the period 1980 -2100 exceeding 5th percentile baseline daily flow under (upper) RCP4.5 and (lower) RCP8.5.

The strongest changes in water availability were observed for RCP8.5 with a pronounced surplus in Northern Europe and a strong decrease in Southern Europe, especially on the Iberian Peninsula where reductions of more than 50% were found. The default climate model (HadGEM2-ES_RCA4) represents the dry extreme or is close to the dry extreme across Europe (Figure 3.2). The wet extreme would lead to unchanged water availability in Southern Europe and an additional increase in water availability by 5% (Northern Europe) to 25% (Eastern Europe).

As the dynamics of changes in water availability over the 21st century show either a monotone increase (Northern and Eastern Europe) or decrease (Southern Europe) or near constant water availability (Western Europe) under RCP8.5, the pattern of change is similar in earlier periods (e.g. 2020s or 2050s) except for a lower magnitude of change (Figure 3.2). The same is true for RCP4.5 in Northern and Southern Europe, while a wetter or drier extreme of simulated water availability was observed in the middle of the century for Eastern and Western Europe, respectively. RCP2.6 differs from this pattern in Southern Europe where a small increase in water availability is projected for the 2080s following an initial decrease in the beginning of the century. Hence, the direction of change depends on the time period.

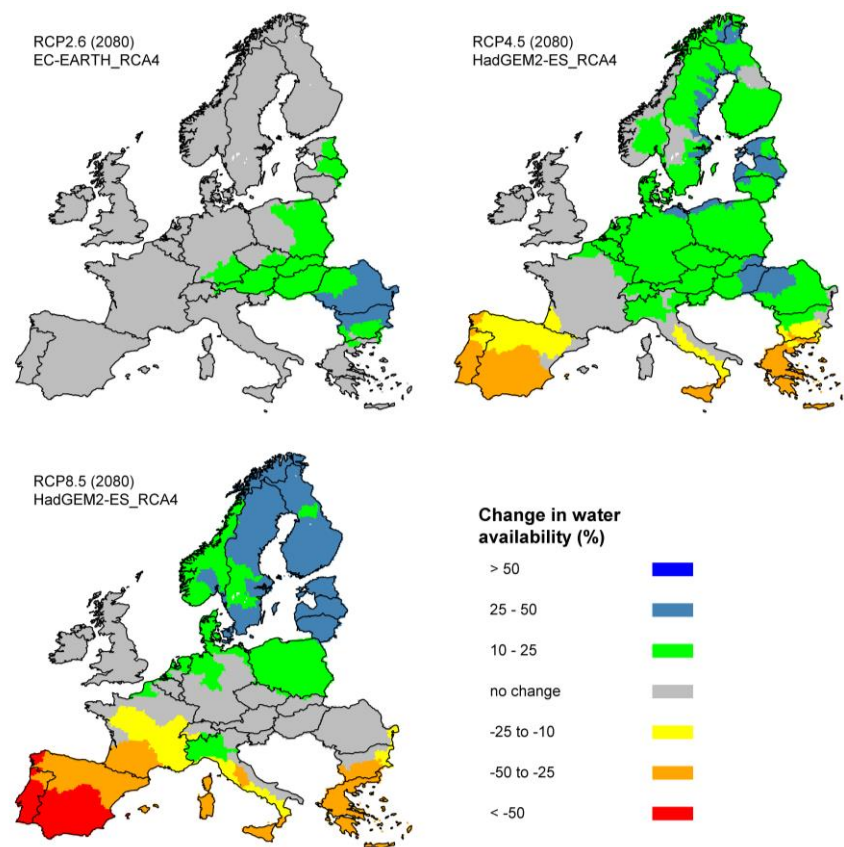


Figure 3.1: Change in annual water availability at the river basin level in the 2080s as modelled by WGMM for RCP2.6, RCP4.5 and RCP8.5 using outputs from the default climate model.

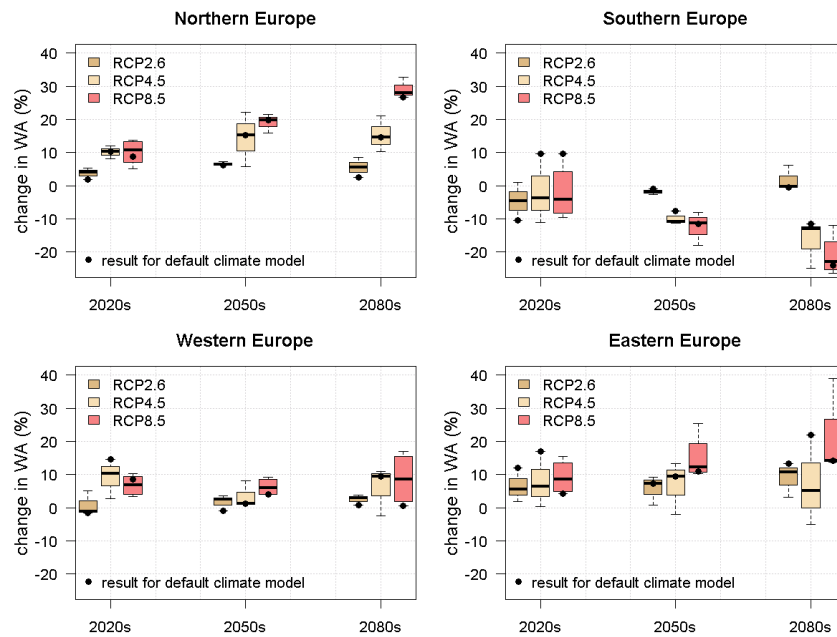


Figure 3.2: Relative changes in water availability (WA) by European region as modelled by WGMM for the climate model ensembles under RCP2.6, RCP4.5 and RCP8.5. Results for the default climate model per RCP are identified (black dot).

In order to determine water stress levels on a river basin level, water withdrawals need to be modelled in addition to water availability. WGMM computes water withdrawals in the domestic, manufacturing, and electricity generation sectors and, via the link to the agricultural sector model SFARMOD. Based on projections of sectoral water demand, the model calculates restricted water use estimates assuring that total water consumption, corresponding to the withdrawals via fixed conversion factors, does not exceed the water availability (see Wimmer et al. 2014 for a detailed description of the approach).

Projections of water demand in the domestic, manufacturing and energy generation sectors in WGMM are based on observed values for the year 2005 which are scaled according to scenario assumptions on change in population, water savings due to technological improvements and behavioral change, GDP, manufacturing gross value added, and thermal electricity production (Table). Restricted water consumption in agriculture (=irrigation) is determined by SFARMOD based on an estimate of the maximum allowable irrigation water consumption provided by WGMM. SFARMOD iteratively increases the price for irrigation water until the extent of irrigated agriculture, which is driven by profit maximisation, is reduced so that irrigation water consumption is equal to the maximum allowable value or below. Hence, water use in agriculture depends on all inputs determining the economics of agriculture. Strongly limited water availability for agriculture may lead to zero irrigation even under dry climate conditions as irrigation may be unprofitable due to water prices. In contrast, reductions of water use or water savings in other sectors may increase irrigation water use because the resulting increase in water supply for agriculture makes irrigation more profitable (rebound effect).

Table 3.2: Socio-economic inputs to WGMM given as percentage change compared to 2005.

Input parameter	Year	SSP1	SSP3	SSP4	SSP5
Population (positive values → increasing domestic water use)	2020	9	-4	3	17
	2050	11	-20	-6	37
	2080	0	-38	-22	47
Water savings due to technological improvements (positive values → decreasing manufacturing and cooling water use)	2020	0	0	0	29
	2050	29	29	29	29
	2080	45	0	29	29
Water savings due to behavioral change (positive values → decreasing domestic water use)	2020	0	0	0	0
	2050	22	0	0	0
	2080	52	0	0	-30
GDP (positive values → increasing domestic water use)	2020	76	39	68	106
	2050	173	51	144	334
	2080	259	48	200	724
Manufacturing GVA (positive values → increasing manufacturing water use)	2020	38	39	102	159
	2050	87	51	216	501
	2080	130	48	300	1086
Thermal electricity production (positive values → increasing cooling water use)	2020	3	-1	16	17
	2050	-13	30	30	98
	2080	-27	52	26	48

Figure 3.3 shows the total water use in Europe and subdivisions for four European regions for the base year 2005 and the projections in the 2080s. As can be seen in Figure 3.3, water use mainly depends on the socio-economic assumptions. The smallest increase was observed for the SSP4 scenarios with roughly a doubling of water use by the 2080s. The highest increase was found for the SSP5 scenarios with water use growing by a factor of four. Projections of water use under SSP1 and SSP3 lie between these extremes with an increase of about 140 % (SSP1-RCP2.6) to 190% (SSP3-RCP4.5).

The choice of the RCP in combination with a given SSP leads to minor variations in projected water use. For example, RCP8.5 leads to less water use than RCP4.5 in combination with SSP3. This is mainly due to a stronger decline in irrigation water supply in Southern Europe for RCP8.5 which overcompensates increasing irrigation in Northern Europe triggered by warmer climate conditions.

In combination with SSP1, RCP4.5 leads to more water use than RCP2.6 because of higher irrigation water demand in Western and Eastern Europe for RCP4.5 due to warmer and dryer conditions, while water availability allows for an increase of irrigation water use.

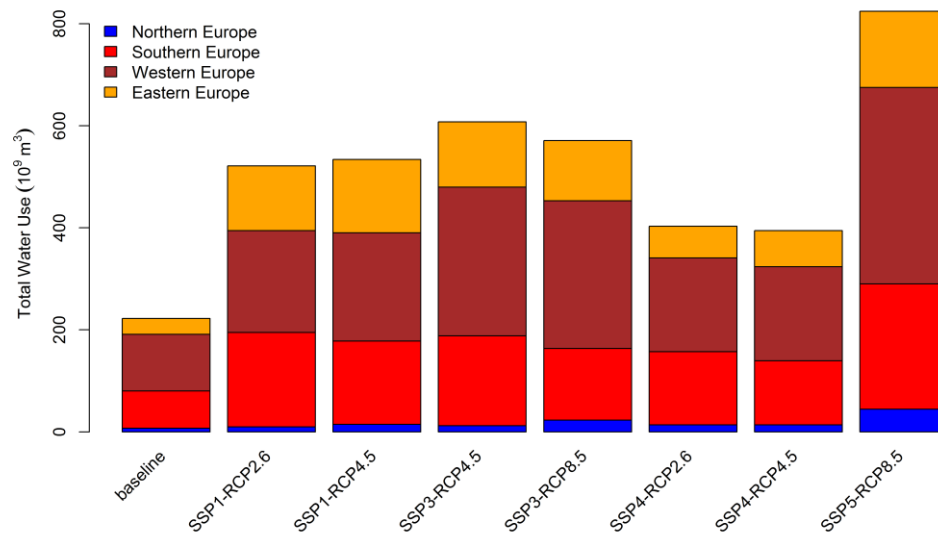


Figure 3.3: Total water use (withdrawals) in the baseline and the 2080s calculated by WGMM.

Given the socio-economic assumptions, it is not surprising that SSP5 and SSP3 lead to the strongest increase in water use, mainly because the manufacturing and electricity sectors grow considerably. However, a closer look is needed to understand the differences between SSP1 and SSP4. Figure 3.4 and Figure 3.5 show trajectories of regional sectoral water use until the end of the century for SSP1 and SSP4, both combined with RCP4.5. The change in domestic water use shows similar dynamics but for different reasons. Population growth is more than compensated by water savings in SSP1 leading to similar effects as negative population growth in SSP4 without significant changes in water savings. In contrast, industrial water uses, i.e., the sum of manufacturing and cooling water use, show opposing dynamics. In SSP1, changes in manufacturing water use are small because the growth in GVA is compensated by water savings due to technological improvements. The stronger growth in GVA under SSP4 leads to a significant increase in manufacturing water use as water savings are less. Cooling water use is declining due to decreasing thermal energy production (TEP) in SSP1 while increasing TEP in SSP4 is only compensated by water savings due to technological change leading to near constant cooling water use in SSP4. Given the same water availability in both scenarios, declining industrial water demand leads to a strong increase in irrigation water supply in SSP1 triggering a disproportional increase in irrigation water use promoted by favorable conditions for the agro-economy. In SSP4, irrigation water supply is reduced by increasing industrial water demand. This, in combination with less food demand (negative population growth) and overall poor economics, leads to moderate irrigation water use.

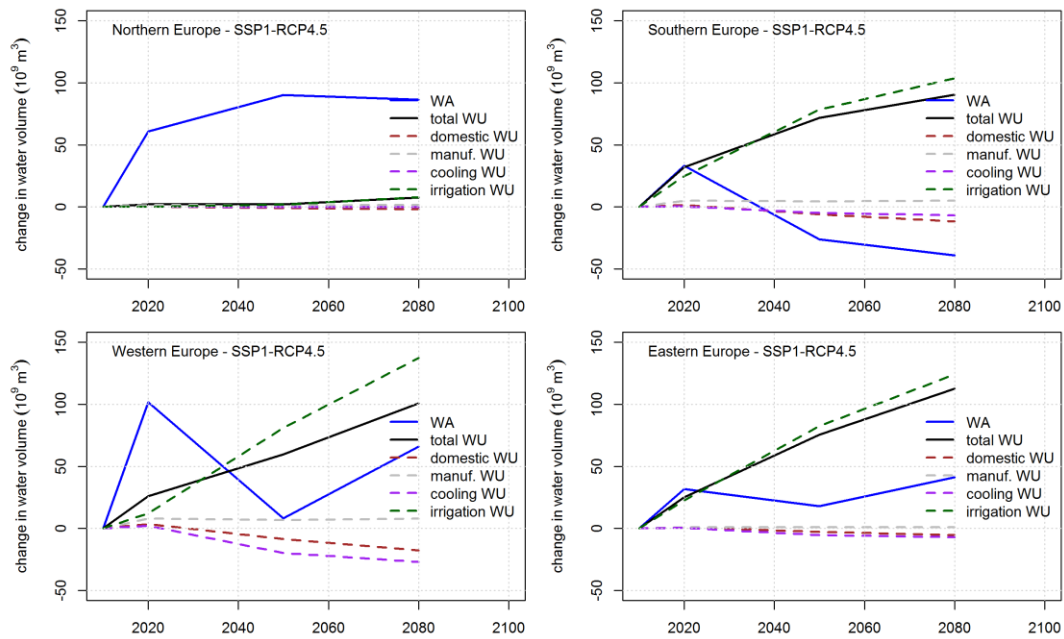


Figure 3.4: Trajectories of change in sectoral water use and water availability as compared to the baseline by European region for SSP1 x RCP4.5.

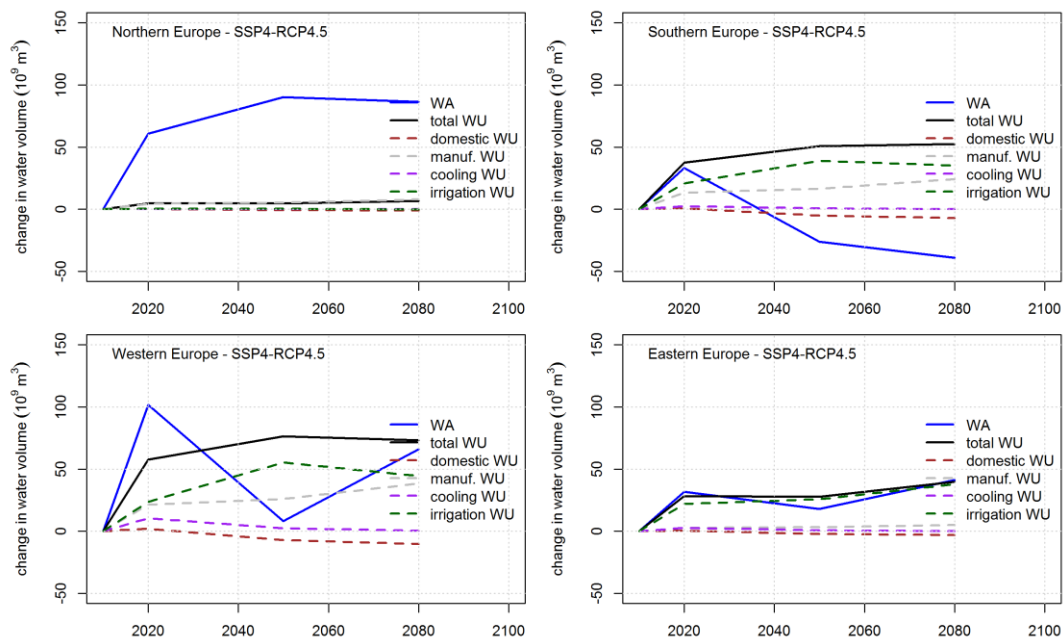


Figure 3.5: Trajectories of change in sectoral water use and water availability as compared to the baseline by European region for SSP4 x RCP4.5.

Based on water availability and total water use, WGMM calculates the water exploitation index (WEI), i.e. the ratio of water withdrawals to water availability, which expresses the pressure on natural water resources. Larger values indicate a greater probability of pollution or depletion. Values of $WEI > 0.4$ indicate severe water stress. In order to compare water stress across the seven SSPxRCP scenarios, Figure 3.6 shows the number of river basins with severe water stress for Europe and the four European regions. On the European level, the changes in the number of basins with severe water stress are

dominated by the results on total water use. In the baseline, severe water stress is only found in Western and Southern Europe. By the 2080s, severe water stress also develops in Eastern Europe in all scenarios and even in Northern Europe for the most extreme scenario SSP5 x RCP8.5. In this scenario roughly every other river basin in Europe suffers from severe water stress compared to every tenth river basin in the baseline.

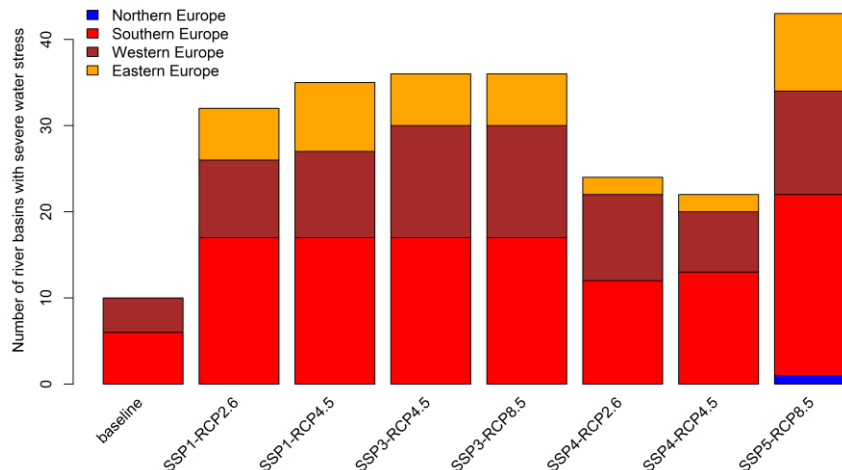


Figure 3.6: Number of river basins in Europe and European regions with severe water stress in the baseline and the 2080.

An index of vulnerability to water over-exploitation is calculated by IAP2/riAM based on WEI and a modelled indicator for coping capacity (see. Dunford et al. 2015). Coping capacity (CC) is derived from human, social, financial and manufacturing capital and ranges between 0 (no coping capacity) and 1 (very high coping capacity). It is assumed that regions with $WEI < 0.2$, the lower threshold for coping, are “not vulnerable (insignificant impact)”. Values of $WEI > 1$, the upper threshold for coping, are assumed to be too high to cope with and, hence, regions with $WEI > 1$ are “highly vulnerable”. For $0.2 < WEI \leq 1.0$ (coping range), it depends on the coping capacity whether the region is vulnerable or is able to cope with the impact. Regions with WEI in the coping range are assumed to be “vulnerable (insufficient CC)” if $WEI > 0.2 + CC \cdot (1 - 0.2)$. All other regions are defined “not vulnerable (sufficient CC)”. Figure 3.7 shows the number of river basins vulnerable to water over-exploitation (“highly vulnerable” and “vulnerable (insufficient CC)”). Due to available coping capacity, the number of vulnerable river basins is lower than the number of river basins with severe water stress. In terms of vulnerability the ranking of the scenarios is different to that in terms of impacts. The most prominent example is SSP5 x RCP8.5, which has by far the largest number of severely water-stressed basins. However, only about two thirds of the river basins with severe water stress are vulnerable to water over-exploitation in this scenario. This is because of the high amounts of human, social and financial capital in the scenario leading to high coping capacity.

In order to compare the regional variability of vulnerability to water over-exploitation across scenarios, Figure 3.8 displays maps of the vulnerability indicator. In the baseline, only six basins are identified as being vulnerable. These are located in dry regions (Spain, Portugal) and Western European regions with high water use intensity (Benelux Countries). By the end of the century, additional vulnerable basins appear predominantly in the dry regions of Southern and Eastern Europe and in Western Europe where water use is highest. Northern Europe stays in the region with no vulnerability in all scenarios.

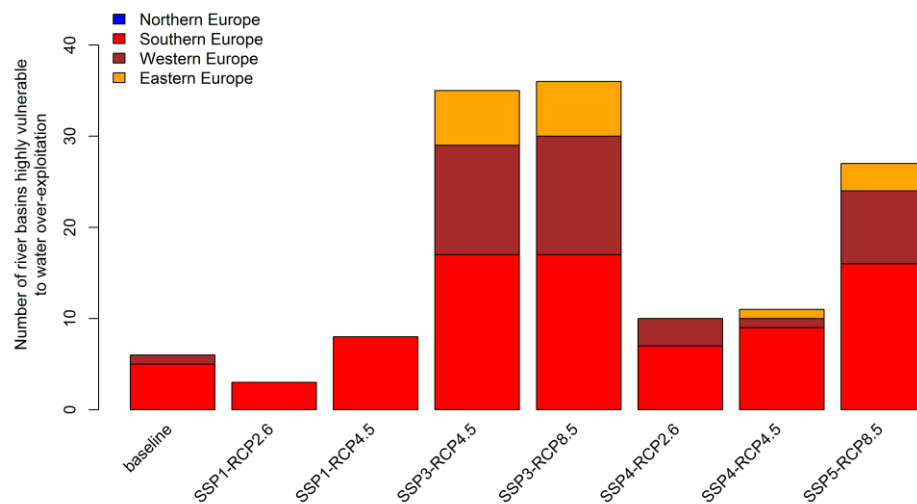


Figure 3.7: Number of river basins in Europe and European regions vulnerable to water over-exploitation in the baseline and the 2080.

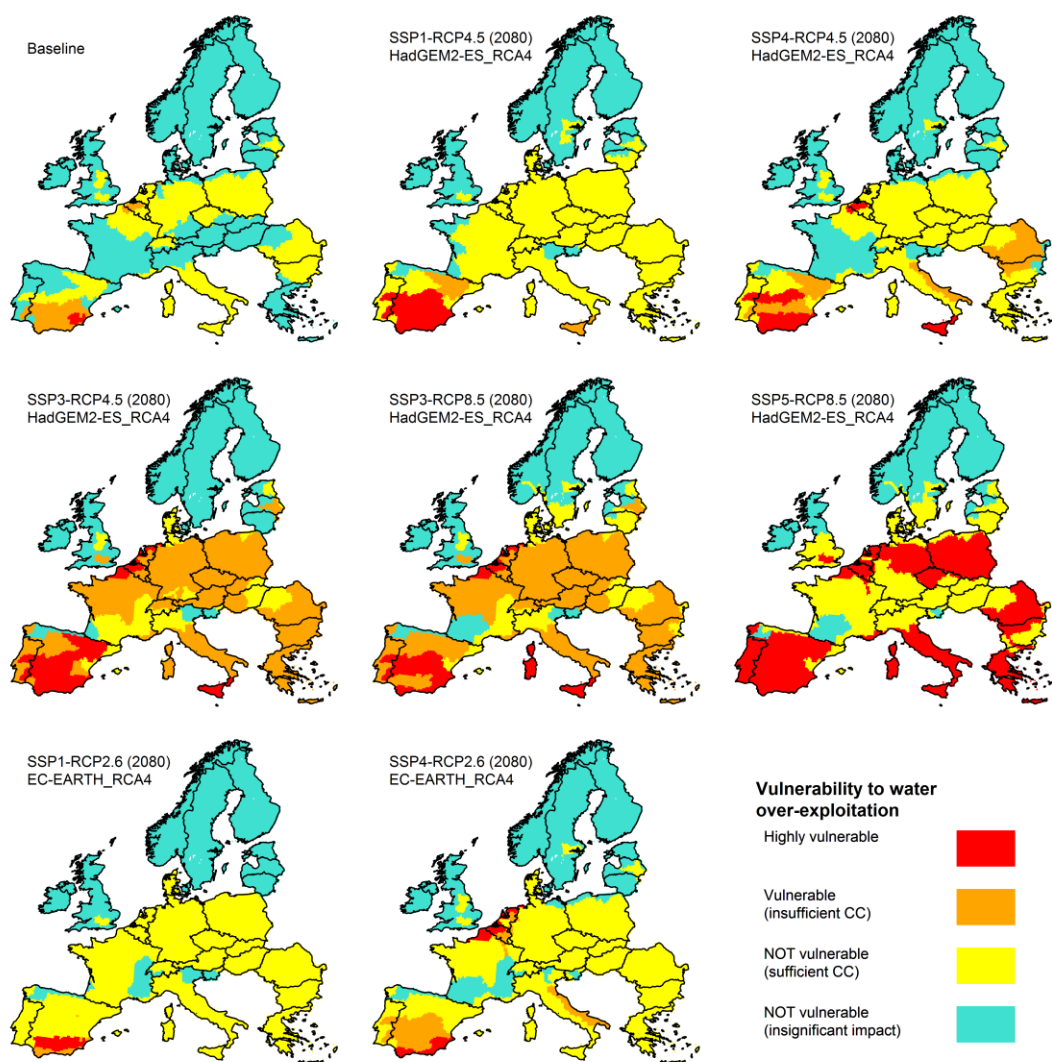


Figure 3.8: Maps showing the indicator of vulnerability to water over-exploitation of a river basin level for the baseline and all scenarios in the 2080s.

3.3. Human health and wellbeing

Extreme weather has significant impacts on economic sectors, as well as adverse social and health impacts on European populations. The impacts of high-end climate change on human health and wellbeing have been evaluated from three different perspectives within the IMPRESSIONS European case study. These relate to the direct impacts on people from flooding and mortality from high temperatures, and indirect impacts due to vulnerability to food provision.

3.3.1. Impacts and vulnerability of people to flooding

Socio-economic impacts of flooding are estimated using the CFFlood model considering combinations of RCPs and SSPs as shown in Table . The four selected socio-economic impact indicators are: (1) area at risk within 100 year floodplains (km²), (2) number of people at risk within 100 year floodplains (millions), (3) number of people flooded in 100 year floodplains (millions), and (4) flood damage in 100 year events (€billions).

The analysis in this section mainly focuses on the changes of the four impact indicators at three time slices (i.e. 2020s, 2050s, and 2080s) from the 2010 baseline year following the IAP2. The results cover impacts of both coastal and fluvial flooding and are presented at the European level.

The area at risk due to coastal and fluvial flooding in a 100-year event at the 2010 baseline year is estimated at approximately 212 thousand km² (Figure 3.34). This number is projected to increase in the 2020s by almost 1.3%, in the 2050s by 2.5% and in the 2080s by 4.1% due to rising sea levels as well as changes in river flow following the HadGEM2-ES_RCA4 climate model. The lowest increase in this indicator is projected at almost 1% by the EC-EARTH_RCA4 climate model while the highest increase is projected in the 2080s at 6% by the IPSL-CM5A-MR_WRF climate model. These changes can be explained by a consistent pattern of increase over time in coastal zones due to sea-level rise, while fluvial flooding varies spatially following the variation in QMEDs across river basins in Europe.

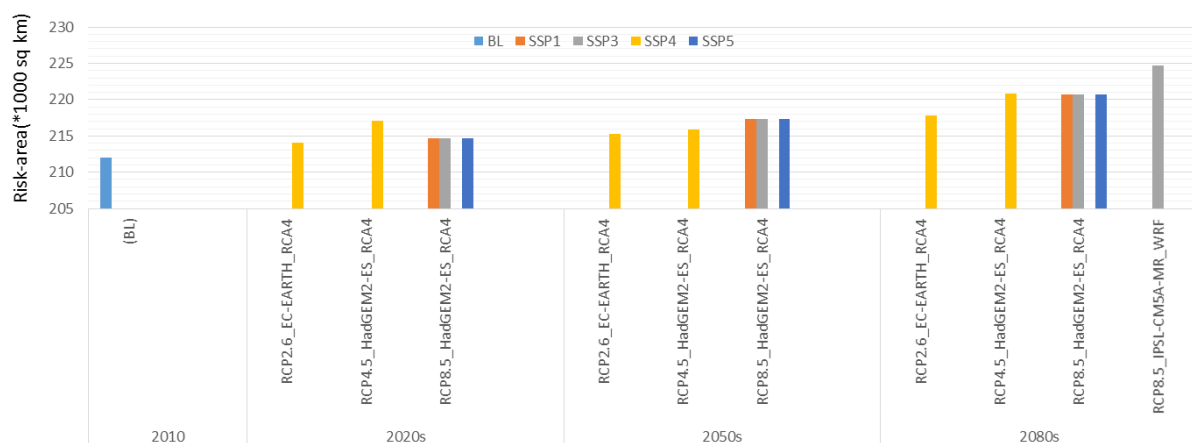


Figure 3.34: Area at risk of coastal and fluvial flooding in a 1 in 100 year event (1% probability of occurrence) under the selected scenario combinations.

The European total number of people within the 100 year floodplains (i.e. coastal and fluvial) is projected to change as shown in Figure under the RCP x SSP combinations. Increases in climate drivers lead to increases in properties at risk of flooding, while changes in population under the European SSPs may exacerbate or diminish this indicator depending on whether increases or decreases in

population are projected, respectively. The highest increase in the number of people at risk of flooding is projected to be 53% in the 2080s under the RCP8.5 x SSP5 combination. In contrast, future socio-economic projections in SSP3 lead to a 33% decline in the number of people at risk relative to the 2010 baseline year. These results highlight that future projections can be sensitive to socio-economic changes as well as climate change.

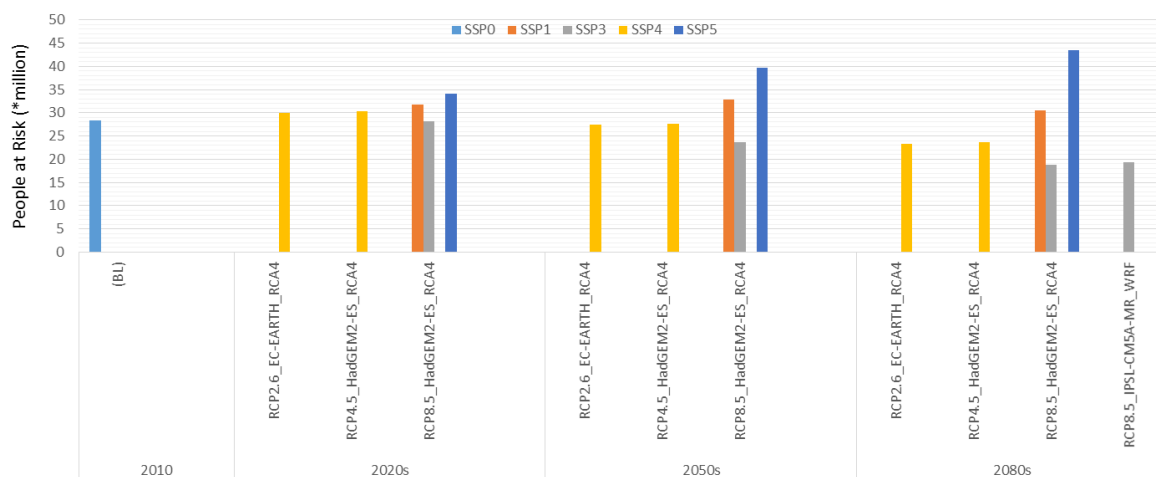


Figure 3.35: People at risk of coastal and fluvial flooding in a 1 in 100 year event (1% probability of occurrence) under the selected scenario combinations.

The number of people affected by flooding can be influenced by the number of people living in flood risk zones (i.e. floodplains) but mainly by the level of flood protection available in these zones. An indicative flood protection dataset at the European level is constructed in the CFFlood model, where ranges of Standard of Protection (SoP) of coastal and fluvial flood defenses are determined based on land use/cover classes and the economic value of the land. The resulting flood protection dataset has been revised using published data on flood protection in individual regions/nations including Belgium, the Netherlands, Northern Germany and London (Mokrech et al. 2015).

The number of people affected by 100 year coastal and fluvial flood events at the 2010 baseline year is estimated at 17.2 million (Figure). This number is estimated to increase in the 2020s under the RCP8.5xSSP3, RCP2.6xSSP4 and RCP4.5xSSP4 scenario combinations and then decline in the 2050s and 2080s to a level that is lower than at the baseline year. This is a reflection of the effect of the population trends on this indicator under SSP3 and SSP4 despite the potential increases in climate drivers (i.e. sea-level rise and precipitation). On the other hand, the number of people affected is estimated to increase to 22.3 million in the 2080s under the RCP8.5xSSP1 climate and socio-economic conditions; and it is estimated to reach the highest level of 32.6 million in the 2080s under the RCP8.5xSSP5 scenario combination. Under these extreme scenario combinations additional flood protection (e.g. building new or upgrading existing flood defenses) should be considered.

Flood damage will increase from the baseline year level under all future scenarios especially SSP3 and SSP5 (Figure). The change in GDP is used in the CFFlood model to reflect changes in the economic conditions and how flood damage is influenced by such changes. The economic damage is estimated at €78 billion for the 100 year flood events. Without flood protection the flood damage is estimated to reach €236 billion; these numbers demonstrate the benefits of flood protection. In essence, these numbers and analysis suggest that Europe has responded to some degree to current flood risk levels. However, future flood risk may grow with climate change, sea-level rise and socio-economic growth, which require more aggressive adaptive measures.

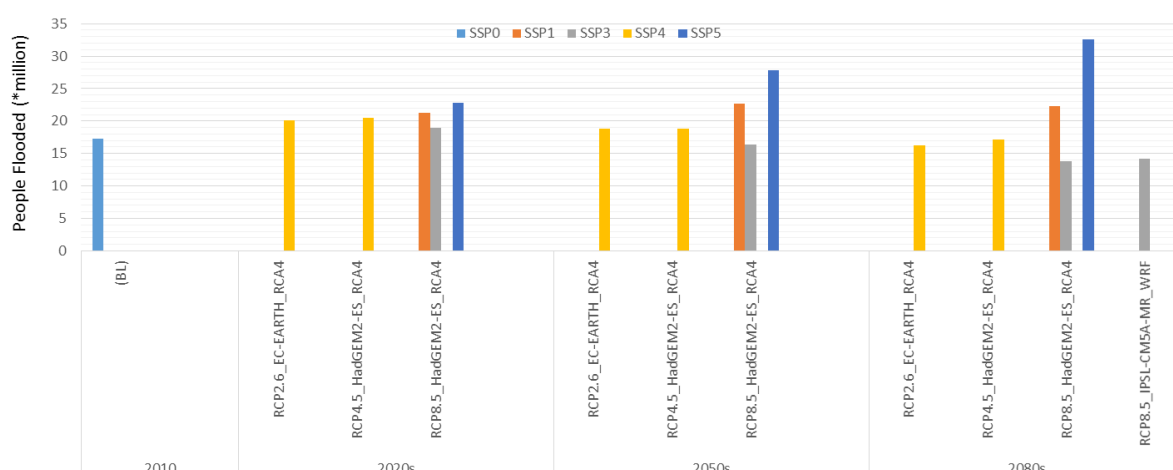


Figure 3.36: People affected by coastal and fluvial flooding in a 1 in 100 year event (1% probability of occurrence) under the selected scenario combinations.

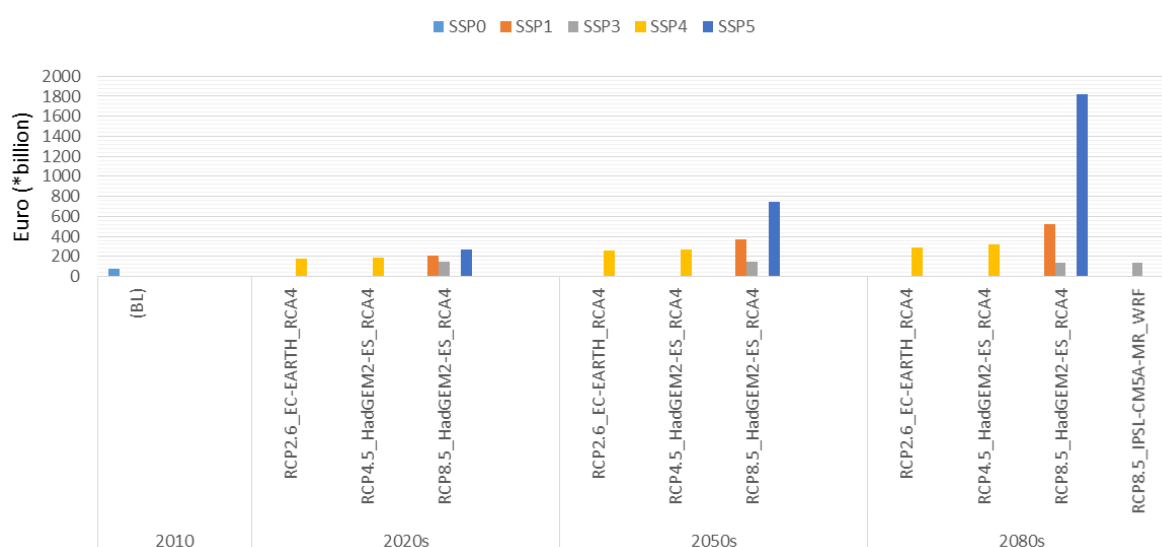


Figure 3.37: Flood damage (Billion €) in a 1 in 100 year event (1% probability of occurrence) under the selected scenario combinations.

3.3.2. Health impacts

Climate change will increase the frequency and the intensity of hot weather - which is associated with significant acute impacts on mortality and morbidity. All populations in Europe are affected by high temperatures, but it is not known how quickly populations can adapt or the limits to this adaptation. The majority of the health burden from high temperatures is experienced by the older age groups. However, high temperatures are likely to have future effects on the capacity to undertake activities outdoors - whether for leisure or employment – which will effect adults and children, as well having socio-economic implications. There will also be health benefits from milder winters in terms of the reduction of cold related mortality or morbidity.

The mortality effects of high ambient temperatures have been estimated using two different models considering combinations of RCPs and SSPs as shown in Table . The single indicator is heat-related mortality (that is the annual number of deaths attributable to above-threshold temperatures) presented in both absolute and relative terms. Age-specific mortality impacts were also calculated for three age bands (0-64, 65-74 and 75 and over), but only total mortality is presented here. The HEET model estimates mortality burdens at the 10' grid level using population data from the RUG urban model within rIAM (see Section 3.1.4). The findings in this section are a summary of the model results on changes in heat-related mortality at decadal time slices from the 2010 baseline year. The results are the combined effect of population growth, population ageing, population movement (within NUTS2 areas, as specified by RUG) and increasing temperatures. They are presented as summaries for five European regions.

Climate change is projected to increase heat-related mortality in all countries in Europe, but impacts are greatest under the high-end scenarios (indicated by the RCP8.5 emissions scenario). Results are presented as absolute annual numbers and not rates meaning population size needs to be taken into account. Figure 3.38 illustrates the future burdens without adaptation are very different across Europe, with Southern and Central Europe showing particularly large increases in heat-related mortality. As would be expected, the impacts are greatest under the highest warming (RCP8.5) and towards the end of the century. The impact of climate variability is also apparent as the model is sensitive to the number of days that occur with temperatures above a location-specific threshold. This model projects higher estimates of mortality effects than models that use a linear association to model the association between temperature and mortality. The model applies non-linear observed temperature-mortality associations that are extrapolated beyond the observed temperature range. The high impacts in Southern Europe reflect the current sensitivity of these populations to higher temperatures.

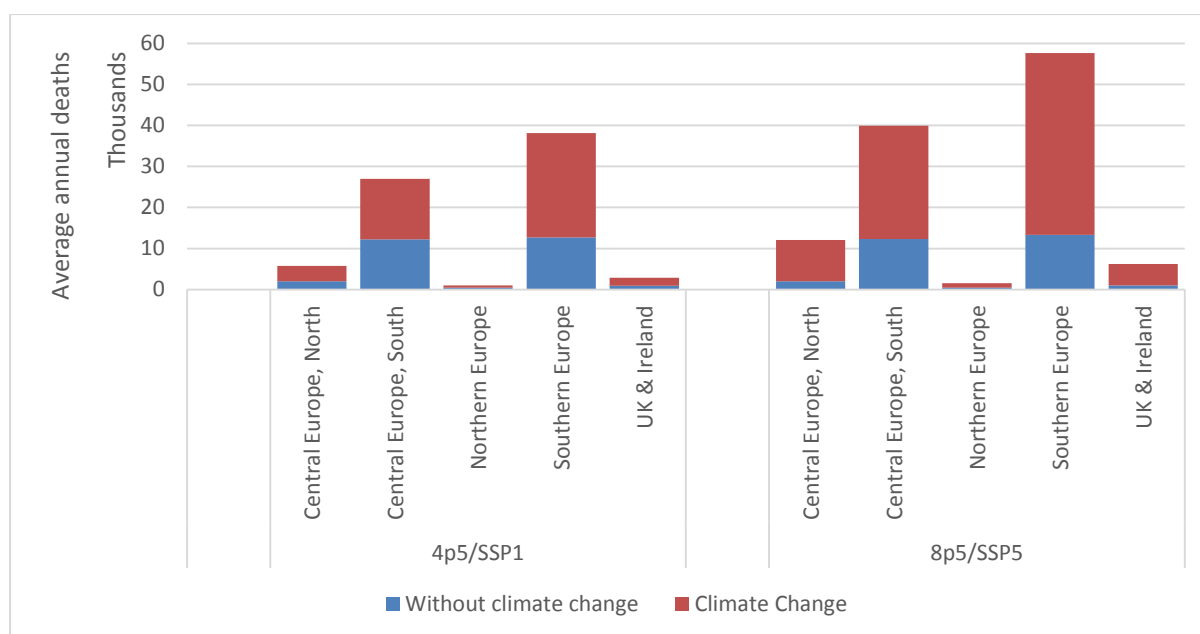


Figure 3.38: Heat mortality (annual deaths) for European regions due to changes in temperature and population ageing, without adaptation. (Note: 4p5 refers to RCP4.5 and 8p5 refers to RCP8.5).

Adaptation measures to reduce heat health effects include heat wave plans, improvements in urban planning and housing design (including retrofitting) and social protection measures for older and vulnerable citizens. Future changes in housing and infrastructure have the potential to reduce the regional or local burden of heat-related mortality. Permanent relocation (either within or between countries) due to high temperatures may occur towards the end of the century. There is currently no empirical evidence regarding this effect under the current climate. Therefore, a simple model assumption was used to take acclimatisation (physiological and behavioural) into account. Figure 3.39 indicates that adaptation may have only modest impacts on future heat-related mortality.

Urban heat islands (UHI) are a factor in many urban settlements and refer to the difference in temperatures measured inside and outside the urbanised area. High ambient temperatures have impacts on thermal comfort, productivity, energy use, and human health. Several studies have quantified the role of the built environment in increasing outdoor temperatures. The UHI intensity is typically higher at night than during the day and shows seasonal variation, typically greater in winter than in summer. Results from RUG show that urbanisation trends in Europe are fairly modest under the range of SSP scenarios (see Section 3.1.4). Thus, changes in outdoor temperature due to increases in high density urban areas are not likely to be a key factor for future heat-related mortality.

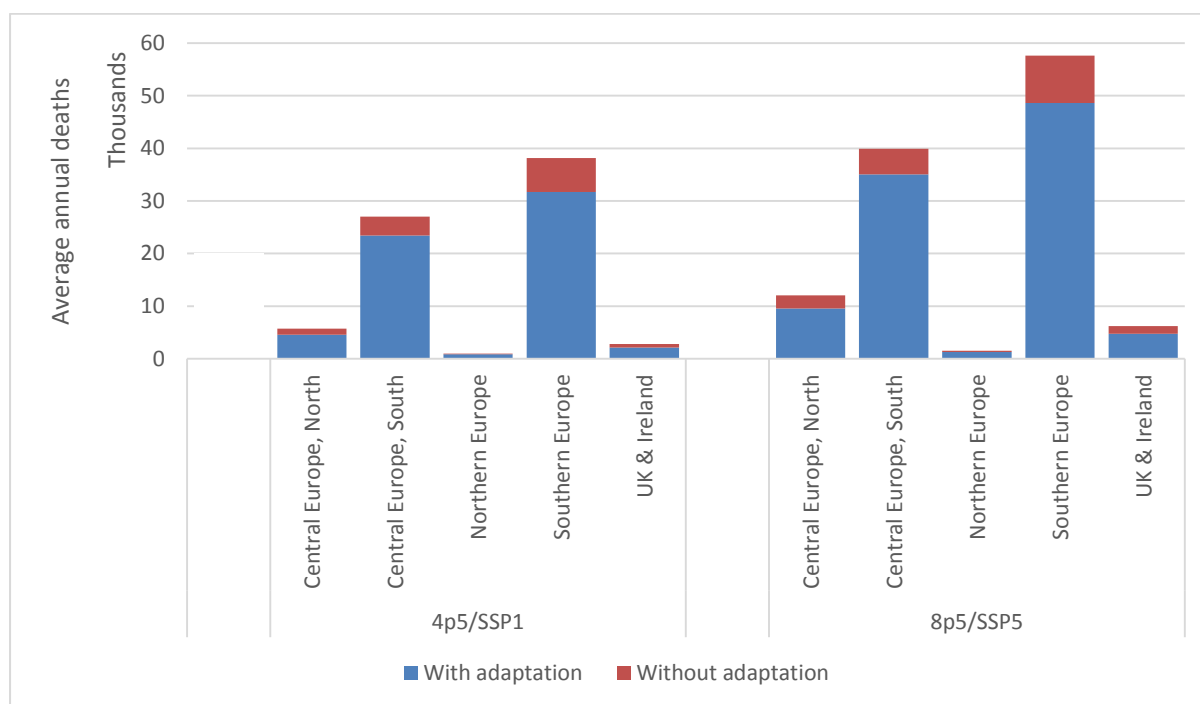


Figure 3.39: Heat mortality (average annual deaths) by European regions in 2050s decade, due to changes in temperature and population ageing, with and without adaptation.

The second heat-mortality model (AIM/Health; Honda et al. 2014) was used to assess the uncertainty around future heat-mortality estimates, which are illustrated with Impact Response Surfaces (IRS). Figure 3.40 shows an IRS for the impacts of temperature and population on heat mortality within the different European regions. This shows that heat mortality increases with increasing temperatures and population. For temperature increases of 10°C, the 30-year maximum heat excess mortality reaches around 100,000 people in northwest Europe (covering northern France [including Paris], the Benelux countries and western Germany) and central Europe (including Poland, Slovakia, Hungary, Romania, etc).

A number of aspects can be drawn out of this analysis that either confirm or are inconsistent with the findings of the HEET model described above. The absolute changes in heat mortality are higher in Northwest Europe (covering northern France [including Paris], the Benelux countries and western Germany) than in Southern Europe reflecting the absolute population size. Consistent with the AIM/Health model, there are strong non-linearities within the response, as shown by the percentage change in heat mortality to changes in both increasing temperatures and population. Finally, the tipping point within the response of heat mortality (as shown by the strong gradient in the percentage change in excess mortality in Figure 3.40 - lower) to increases in temperatures differs between the regions being lowest in the cool maritime climate of the United Kingdom and Republic of Ireland, and the warm Mediterranean climate of Italy and Greece.

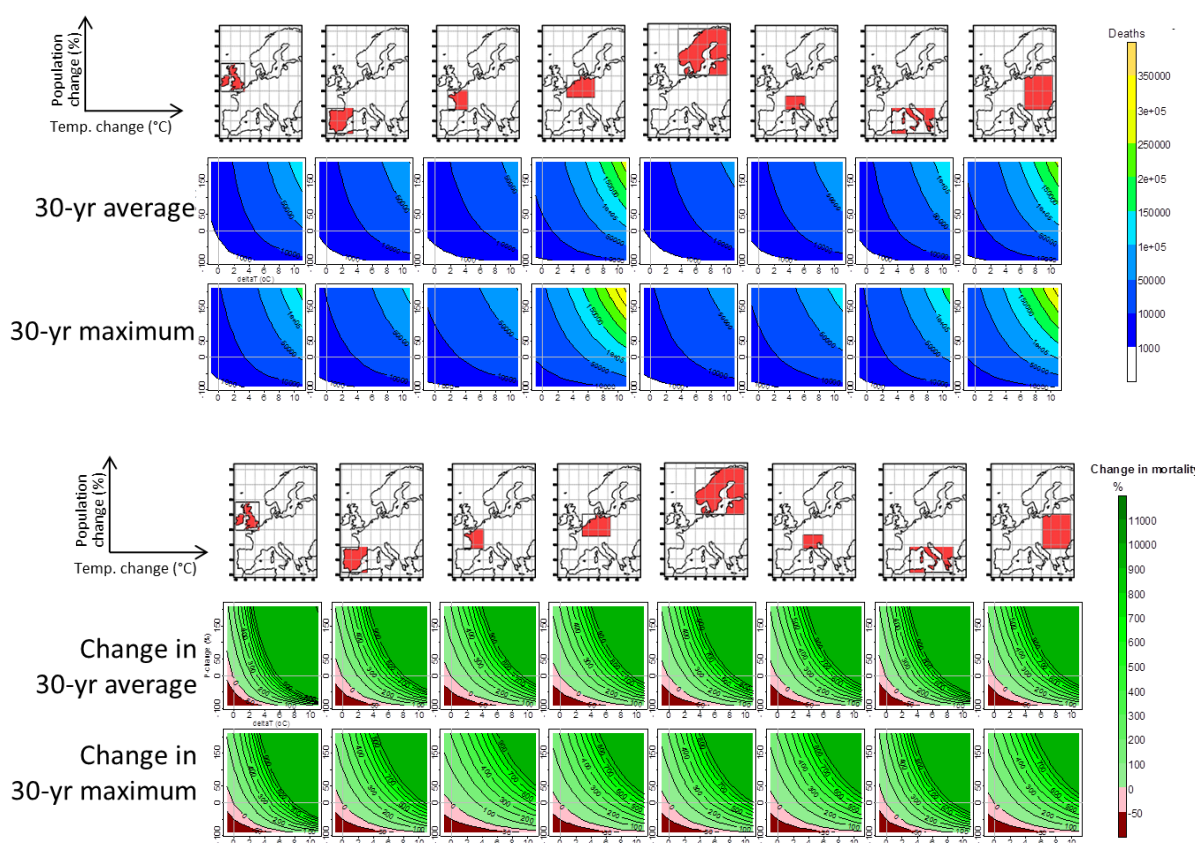


Figure 3.40: Impact Response Surfaces of heat excess mortality (deaths) for European regions to changes in temperature and population: (upper) absolute deaths; (lower) percentage change in heat mortality.

These results show that the impact of climate change on heat-related mortality in Europe is very dependent on future rates of population ageing. Population growth is only a determinant to the extent that the number of older persons is increased. Populations in Europe are ageing, and projections show that the proportion of elderly and very elderly increases in all populations over the century. However, population growth is non-linear in many countries and, particularly in Northern and Central Europe, peaks around mid-century (see Section 3.1.4 for more detailed description of population trends within each SSP). Thus climate change impacts are attenuated in many countries, despite higher rates of warming. Population growth rates remain uncertain, even within Europe. Further, studies of healthy ageing also indicate that there is considerable uncertainty about the vulnerability of Europe's older citizens to weather extremes.

3.3.3. Vulnerability to food provision

The vulnerability of the European population to food shortages can arise at two scales: at a supra-national level, whether the European agricultural system can meet the demand for food from Europe allowing for net imports and, secondly, at a sub-national level, whether the population can access reliable supplies of food. The European case study has evaluated aspects of both of these.

Firstly, Figure 3.41 shows impact response surfaces of the agricultural area within European regions to changes in precipitation, temperature and atmospheric CO₂. The agricultural land-use system model within the IMPRESSIONS IAP2 autonomously adapts to try and meet European food demand by expanding or contracting the agricultural area. It does this by progressively increasing or decreasing prices in order that sufficient land areas become profitable or unprofitable for food production to meet the demand. The Figure shows significant changes in regional agricultural areas as productivity changes in response to changing climatic condition and as regions gain or lose relative profitability. However, the shaded parts of the IRS plot show conditions in which the IAP2 is unable to increase the agricultural area sufficiently to meet demand. In these climatic situations, there would be shortfall in Europe's ability to feed its current population.

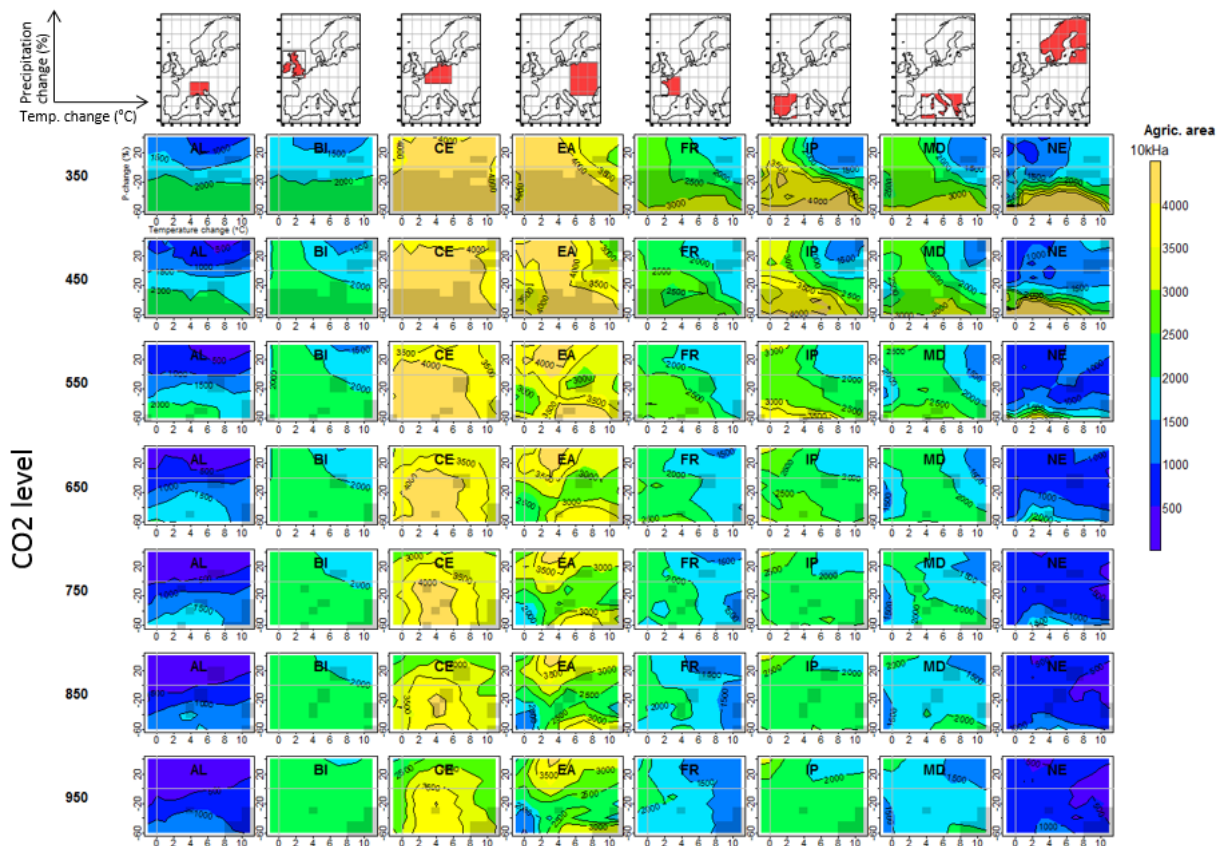


Figure 3.41: Impact Response surface of the agricultural area within European regions to changes in temperature and precipitation (assuming population and other socio-economic variables remain constant) [shaded areas indicate scenarios in which European food demand could not be met].

Table 3.3 indicates whether the food demand within Europe can be met within the different scenario combinations listed in Table 2.3. It is notable that the model is unable to meet food demand under the European SSP1 scenario under both RCP2.6 and 4.5 despite decreases in the dietary preference to

meat, despite the large increases in the agricultural area which are evident in Figure 3.2. This arises due to the decrease in imports and the de-intensification of European agriculture within the scenario. There are only two other scenario combinations in which autonomous adaptation within the European agricultural system to expand production is insufficient to enable European food demand to be met – SSP4 under RCP2.6 in the 2020s and SSP3 under RCP8.5 in the 2020s.

Table 3.3: The simulated ability to meet European food demand for different combinations of climate and socio-economic scenario using the IMPRESSIONS IAP2 default climate models.

Shared Socio-economic Pathway	Representative Concentration Pathway	2020s	2050s	2080s
SSP1	2.6	✗	✗	✗
	4.5	✗	✗	✗
SSP4	2.6	✗	✓	✓
	4.5	✓	✓	✓
SSP3	4.5	✓	✓	✓
	8.5	✗	✓	✓
SSP5	8.5	✓	✓	✓

Finally, vulnerability to food provision can arise at a sub-national level due to the difficulties for the local population to access reliable and affordable supplies of food or for challenges for European food distribution to transport food from areas of production to demand. Figure 3.42 therefore shows two contrasting scenario results for European food provision vulnerability.

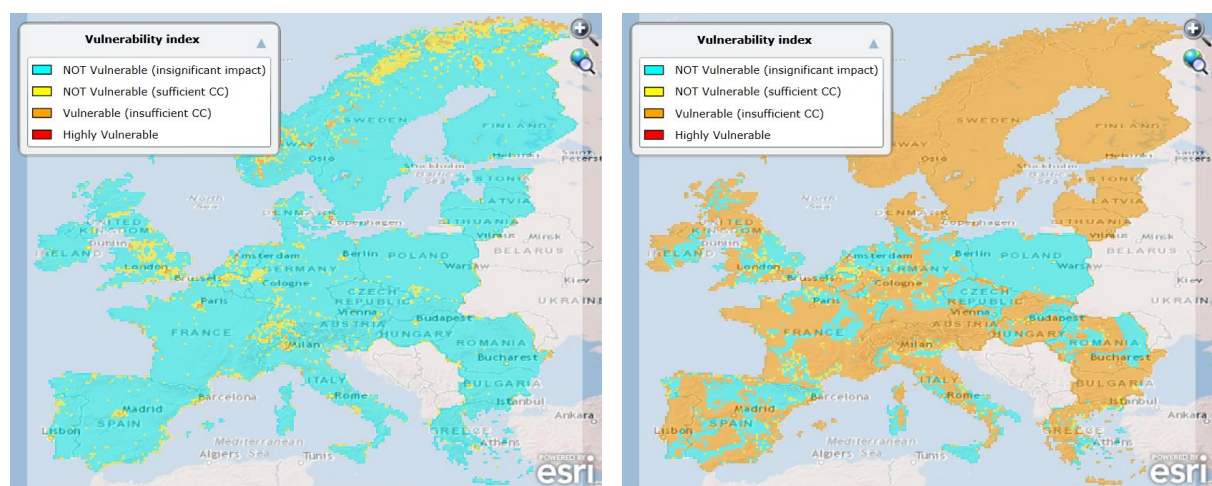


Figure 3.42: Vulnerability for food provision across Europe in 2080s for (left) Eur-SSP1 under RCP2.6 with the lowest overall vulnerable population and (right) Eur-SSP4 under RCP4.5 with the highest overall vulnerable population.

The European SSP1 scenario under RCP2.6 in the 2080s has the lowest vulnerable population, despite the European agricultural system failing to fully meet food demand. This low vulnerability arises from (1) a highly distributed food production system in which the patterns of spatial demand and production are closely aligned; and (2) high coping capacity so that individuals and society have the necessary networks and resources. In contrast, the European SSP4 scenario under RCP8.5 in the 2080s

has the highest vulnerable population, despite all of Europe having high or very high coping capacity. In this case, the vulnerability arises because substantial productivity increases within the European agricultural system have led to a reduced agricultural area. As a consequence, the patterns of spatial food demand and production are greatly mismatched, leaving the population vulnerable to being potentially unable to access sufficient food.

3.4. Biodiversity and habitat

Here we present the analysis of the impacts and vulnerability of species by analysing the change in area that has both suitable habitat and climate under a range of future climates as calculated using the IMPRESSIONS IAP2. The analysis is based on all the 112 species included within IAP2 and looks at the change in total number of species with both climate and habitat space relative to the current numbers present (using the baseline scenario for 1961-90). These species were selected to cover the range of species and habitats within Europe (e.g. wetland, heathland, grassland, forest and farmland species; animals and plants; Mediterranean and alpine species).

Six different regional areas are analysed: (1) the full EU 28 + Norway and Switzerland, i.e. the IMPRESSIONS IAP2 countries; and (2-6) the five IPCC bioclimatic regions within it: Northern, Alpine, Southern, Continental and Atlantic (Kovats et al. 2014). An index is calculated by summing, for a given region the number of species present per grid cell within that region, weighted by the land area with each grid cell and then calculating the relative change in this number relative to the values for baseline. The values presented are therefore proportional (%) change in number of species relative to baseline.

3.4.1. Impacts of sea level rise on coastal habitats

The modelling using CCFlood shows that the environmental impacts on coastal habitats due to sea-level rise can be significant. Figure 3.43 shows the systematic trend of loss in saltmarsh. Under the RCP8.5 scenario, the loss of saltmarsh may reach 70% in the 2080s from the baseline level. Intertidal flats show a similar trend of loss. On the other hand, the area of coastal grazing marsh is mainly an indicative estimate of the potential of this habitat. It is mainly managed habitat and it will change into saltmarsh due to a change in salinity. In river valleys, change in inland marshes is a function of change in river flows where existing marshes can increase or decrease as a function of change in floodplains and management.

3.4.2. Impacts of climate change on combined habitat and climate space for species with baseline socio-economics

Evaluating the impacts of the three RCPs to 2080 in the absence of socio-economic change (i.e. using the same socio-economic settings as at baseline) reveals the potential impacts of climatic change (Figure 3.44). Under RCP2.6 there is a small increase in species with suitable habitat and climate space in the 2050s followed by a similar level to baseline in the 2080s. Conversely, under both RCP4.5 and RCP8.5 the numbers of species with suitable climate space decreases significantly. Under RCP4.5 there is a 5% decrease in species with suitable climate and habitat space by the 2050s, worsening to a 10% change by the 2080s. RCP8.5 sees even greater change – double that seen in RCP4.5 to a maximum loss of > 20% of species by the 2080s. It should be noted that these impacts are across Europe as a whole, taking into account that some species will gain whilst other species will lose and that some may gain in some locations and lose in others.

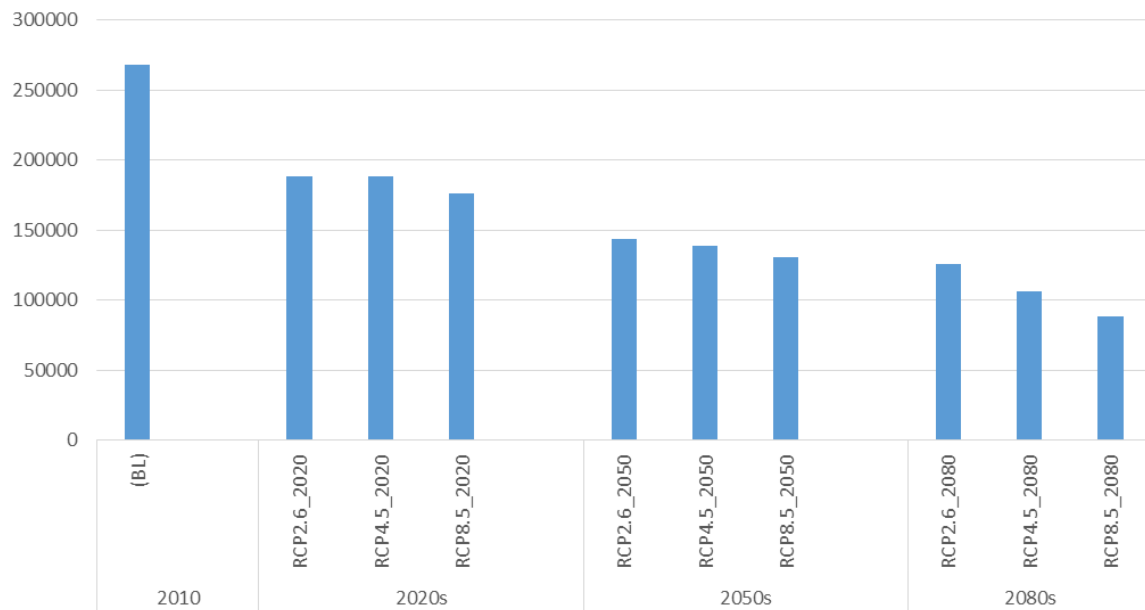


Figure 3.43: Trend of change in the area (hectares) of saltmarsh in the European case study due to sea-level rise.

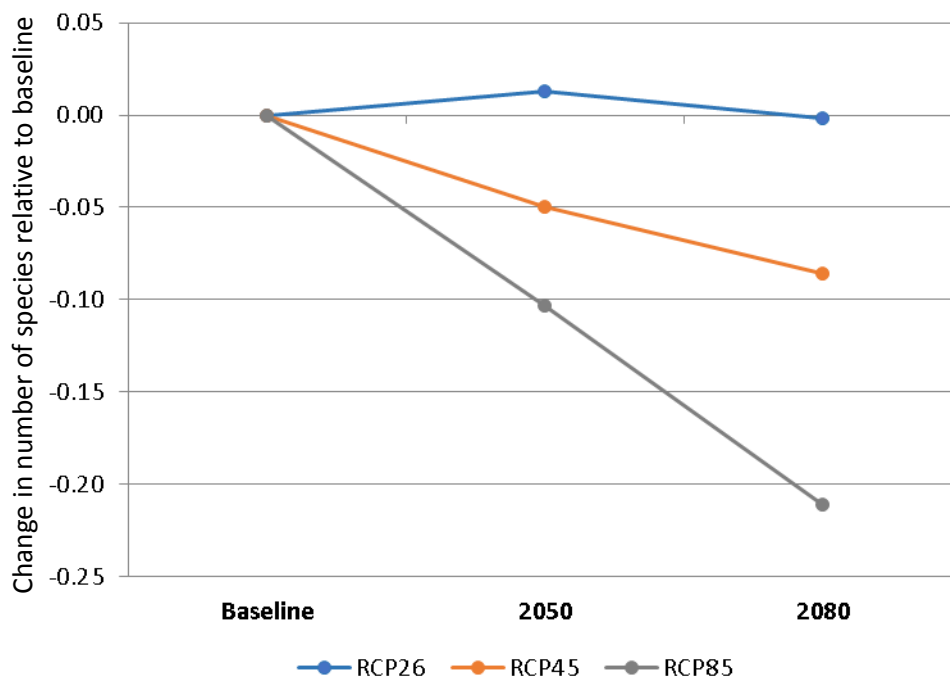


Figure 3.44: Change in total number of European species with appropriate climate and habitat space as a result of climate-only changes. [Climate change with baseline socio-economics; RCP2.6 using the EC-Earth-RC4 model and RCP4.5 and RCP8.5 using HadGEM2-ES_RCA4].

There will also be winners and losers from climate change in terms of significantly differentiated spatial impacts of climatic change (Figure 3.45). This is notable even with lower end climate change: under RCP2.6, in the 2050s, whilst Europe as a whole is gaining climatic space for species, > 15% species lose suitable climate and habitat space in Southern Europe. At the same time, the North is

becoming more suitable with 20% more species in the 2050s with appropriate climate and habitat space than at baseline. It is interesting to note that this increase in the north declines to 13% in the 2080s, suggesting that in RCP2.6 even areas that gain in the short-term may see declines in the future as climates become less suitable, or pressures on land use from climate changes elsewhere necessitate habitat changes in the north. Regional differences are even more notable under more extreme climates: with RCP8.5 there is a 40% increase in modelled species by the 2080s in Northern Europe, whilst Southern Europe shows a loss of 60% of the modelled species.

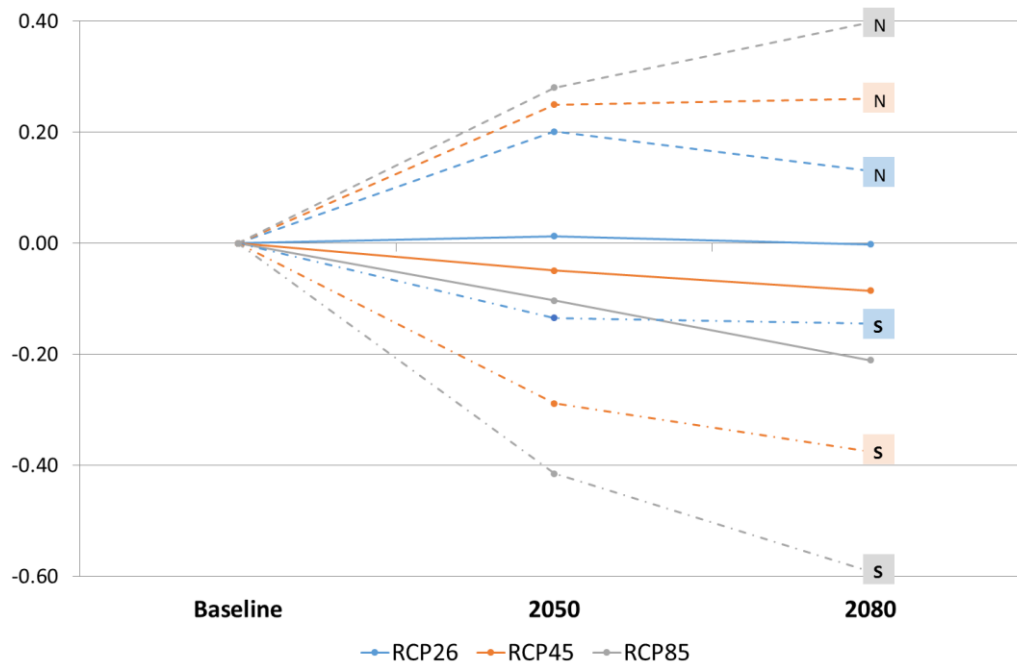


Figure 3.45: Regional differences in change in total number of European species, and those for the Northern and Southern regions. Figure shows appropriate climate and habitat space as a result of climate-only changes with time. Dashed lines marked N are for the IPCC Northern Europe region; dash-dotted lines marked S are for the IPCC Southern Europe region. Climate change with baseline socio-economics; RCP2.6 using the EC-Earth-RC4 model and RCP4.5 and RCP8.5 using HadGEM2-ES_RCA4.

3.4.3. Impacts of socio-economic change on simulated species presence

Different socio-economic conditions (SSPs) can lead to significant changes in terms of impacts to biodiversity than those that result from climatic changes alone (Figure 3.46). Both SSP1 and SSP4 scenarios lead to a significant decrease in species with suitable habitat. These reductions result from habitat changes; e.g. in SSP1 where there is a significant improvement in agricultural technology and productivity, but there is not a focus on planting climatically appropriate trees and there is a significant increase in population (+11% in 2050) and European food self-sufficiency (imports -11% in 2080) leading to a considerable shift from the modern day distribution of land use. As a result, under SSP1 there is a significant loss in forestry and expansion of agriculture (albeit low input sustainable agriculture) into extensive grassland areas. This considerably restricts the available habitat for species and is reflected by a 12% decline in species relative to the scenario with baseline socio-economics. Similarly, under RCP4.5 climate there are no SSPs that lead to an improvement in habitats relative to current baseline socio-economics with decreases of an additional -1-2% resulting from SSPs 1, 4 and 5. SSP3 shows greater declines (-7% more species relative to baseline socio-economics under the same

scenario). This is a result of the scenario's decline in agricultural mechanisation and yields; increase in white meat consumption and investment in biofuels leading to greater land use change than the other scenarios.

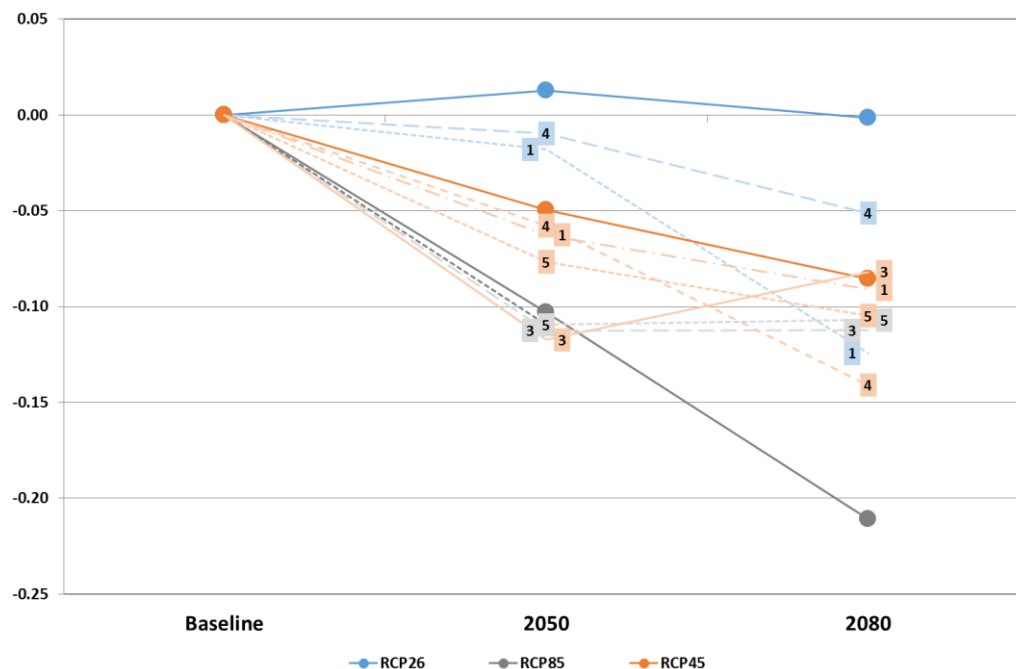


Figure 3.46: The influence of SSPs on changes in total number of European species with appropriate climate and habitat space as a result of climate-only changes with time. Climate change with baseline socio-economics are solid lines, dashed lines illustrate the SSPs and are labelled with their SSP number; RCP2.6 using the EC-Earth-RC4 model and RCP4.5 and RCP8.5 using HadGEM2-ES_RCA4.

In the 2080s, SSP3 performs best out of all scenarios for biodiversity. Unlike SSP4 and 5 which lead to declines of -4% and -1%, respectively, SSP3 shows an increase in species (+1%) relative to baseline. This is because whilst mechanisation doesn't improve between time periods the combination of increasing climatic pressure on resources (e.g. food, timber) and significant declines in population relative to today (-38%) means less overall change in land use minimising the impact on species relative to baseline socio-economics. Conversely SSP4, which also has a significantly declining population (-22%) in the 2080s, has considerable increases in agricultural productivity (agricultural mechanisation +133% and yields +89% from current) that significantly reduces the agricultural area, allowing other land uses to expand, but leading to habitat loss for a number of farmland species: resulting in an additional loss of habitat space for 5% of the modelled species beyond those under the same climate with baseline socio-economics. Finally, it is significant to note that under very high-end climate scenarios (RCP8.5) the two scenario-consistent SSPs (3 and 5) both lead to an improvement in the availability of habitat by providing a wider range of habitat availability relative to a situation where current socio-economic conditions occur under the same climate (c.+10% relative to baseline). The take home messages are (i) that socio-economic drivers can make significant differences to future biodiversity even within the same climate scenario, and (ii) that these changes can be both positive or negative overall – or vary spatially with some locations gaining whilst others lose (Figure 3.47).

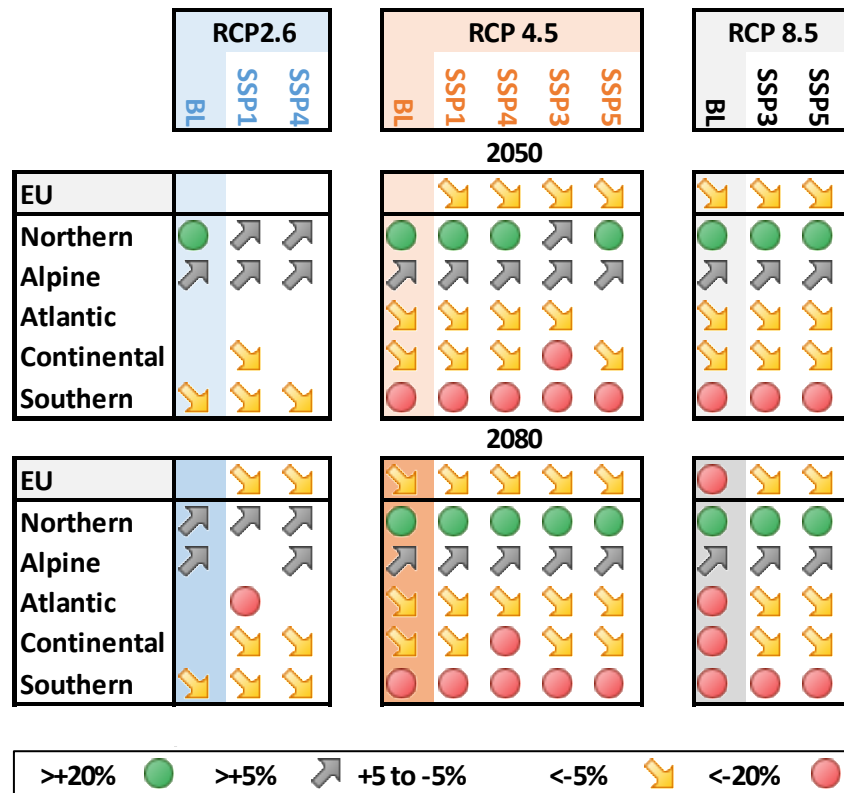


Figure 3.47: Impacts of climate and socio-economic change on the total number of species relative to baseline at a regional level and through time. RCP2.6 using the EC-Earth-RC4 model and RCP4.5 and RCP8.5 using HadGEM2-ES_RCA4.

In the same way that climatic scenarios have differentiated / led to regional differences, socio-economic scenarios not only modify the overall European impact of change on species, but different regions are affected in different ways (Figure 3.47). For example, under RCP2.6 in the continental region there is no loss in overall species numbers with baseline socio-economics: yet, under SSP1 shifts in agricultural production lead to a 5% loss in species in this region. Similarly under RCP4.5, whilst the majority of scenarios show a >23% improvement in species in the north, and losses of 12%, 13% and 18% (SSPs 1,3, and 5 respectively) in the continental region in the 2050s under SSP3 both impacts are worse for biodiversity: the north increases less (+19%) and the continental region decreases more - 21%. This underlines the point that whilst climate may set the direction for the trends, setting in place greater challenges for Southern Europe than Northern Europe, the significance of these impacts will be modified significantly by socio-economic changes.

Limitations to the modelling

The modelling results presented above are drawn from an analysis of 112 selected species. These species were selected to cover the range of species and habitats within Europe. The analysis is performed relative to baseline conditions to take into consideration the fact that there are not the same number of species in every grid cell. However, the results will always reflect to an extent the species selected and their distributions. Secondly, in its current form the IAP2 does not take into consideration the management of land. There will be significant differences between a forest managed solely for timber and one managed to conserve biodiversity, however, the analysis above works on the principle that as long as the land use is present it is possible for a species to make use of

it. In addition, how land set-aside from agricultural production is managed is also not considered within the modelling. In SSP1 for example 6% of land is taken out of agricultural production for nature preservation. However, this set-aside land remains seen as “arable farmland” within the modelling, whereas one might imagine within a scenario such as SSP1 where woodland decline is so notable that there might be some encouragement to allow farmland forests to develop so as not to reduce some of the more extreme impacts of habitat. This is something that is being explored as the biodiversity modelling is further developed within rIAM.

Finally, within the analysis presented there is an implicit assumption that if habitat is available and the climate is suitable the species will be able to reach this area. In reality the ability of that species to move into the new areas will depend on the species’ distribution in the previous time step, and its ability to disperse. New modelling for rIAM will use species distributions from the previous time step and that species’ dispersal information to assess the proportion of newly available climate space that becomes available that the given species will be able to access.

Conclusions

A number of conclusions can be drawn from the biodiversity modelling within the European case study:

- Both climatic and socio-economic changes provide significant potential challenges for European biodiversity;
- The magnitude of these impacts has been modelled to vary between no change under the most optimistic RCP2.6 to a potential decline of 20% of species under high-end climate change (RCP8.5);
- The impact of socio-economic change can both lessen and worsen these impacts as significant shifts in land use from current day distributions will lead to habitat loss;
- The impacts of biodiversity loss are more significant at a regional scale with modelling suggesting that, whilst the Northern Europe may see increases of species up to +40%, Southern Europe may suffer declines in species with suitable habitat and climate space in the region of 60%.

4. Progress towards a Vision for Europe under high-end scenario

This component of the European case study is still in progress in advance of developing the final outputs for the European Stakeholder Workshop #3 in May 2017. This section therefore provides illustrative preliminary results.

4.1. Characterising the Vision

A range of Vision elements have been selected from the stakeholders' Vision for Europe in 2100 that both capture the breadth of the Vision and that exemplify vision elements that would require the implementation of adaptation, mitigation and transformative actions to be successfully implemented in order to achieve them (Table 4.1). To ensure the saliency of the Vision indicators, relevant Sustainable Development Goal indicators are also identified. In recognition of the inevitable limitations of all models to represent such complexity, qualitative (expert-judgment) and quantitative (model-based) approaches are taken to assess the indicator values under current and future conditions.

4.2. Assessing progress against the Vision

The text within each of the European SSP storylines and their associated pathways have been separately analysed (Table 4.2) to identify those components which reflect progress towards or away from the vision element. A preliminary draft numerical score has been identified by expert-judgement to reflect progress towards the desired status of the qualitative vision element indicator (Table 4.2).

In addition, Figure 4.1 shows draft modelled indicators, expressed on a scale of 0-100 where 100 represents the vision element being met. As would be expected, the impacts and vulnerability associated with SSP1 x RCP4.5 are lower than those under the more dystopian SSP3 x RCP8.5. In SSP1, the main vulnerabilities are associated with flooding and food provision, although the latter decreases over time. SSP3 has similar levels of flood vulnerability, but much higher water vulnerability and food vulnerability that progressively increases.

Within the pathways, there are various actions that contribute to addressing these vulnerabilities including actions that increase capital, change dietary preferences, maintain or expand particular land uses, change the relative prioritisation given to water allocation, increase water savings and change the level of intensity of agricultural production. These generally lead to an improvement in the status of most of the modelled vision indicators, although many do not reach the vision target. Whilst the pathways tend to improve the status of the vision element indicators, there are also trade-offs evident – for example, in SSP1, allocating more water to the environment in order to increase the lack of water vulnerability contributes to a small reduction in the lack of food vulnerability in the 2080s as less water is available for agricultural irrigation; whilst actions to increase food productivity (to reduce food vulnerability and to make space available for forest) lead to a reduction in species extent.

Table 4.1: Draft selection of vision elements, indicators and vision indicator target value for the European case study.

Vision element	Text from full Vision	Related SDG indicators	IMPRESSIONS Indicator selected	Modelled or expert interpretation	Vision indicator target value
Voice, equity, and equality					
Wealth duly distributed <i>[transformative]</i>	- Gaps between the wealthy and the less-well-to-do groups in each country are lower than in 2016 - Wealth is duly distributed, globally and regionally. - Poverty is eradicated. - Active mechanisms to counteract the concentration of wealth and power	1.2.1 Proportion of population living below the national poverty line, by sex and age 10.2.1 Proportion of people living below 50 per cent of median income, by age, sex and persons with disabilities	Wealth equality	Expert (storyline and pathway text)	Wealth equally distributed through society
Living and lifestyle					
High quality of life <i>[adaptation]</i>	Sustainable and healthy living patterns Outside these dense areas are large spaces for agriculture, nature, water buffering, productive open space and recreation	3.4.1 Mortality rate attributed to cardiovascular disease, cancer, diabetes or chronic respiratory disease 11.a.1 Proportion of population living in cities that implement urban and regional development plans integrating population projections and resource needs, by size of city	Area not vulnerable to a change in Intensity index (Cultural ecosystem service indicator) <i>[% of Europe]</i>	Modelled	100%
Food, water and energy					
Food security for all <i>[adaptation]</i>	Basic human needs (e.g. clean water, healthy nutritious food, decent shelter, free basic education) are met Sustainable agriculture and fisheries are 100% organic and provide food security for all Quality agricultural clusters satisfy the needs of communities at local and global level	2.1.2 Prevalence of moderate or severe food insecurity in the population, based on the Food Insecurity Experience Scale (FIES) 2.4.1 Proportion of agricultural area under productive and sustainable agriculture	Lack of population-weighted food vulnerability <i>[% of people]</i>	Modelled	100%

Vision element	Text from full Vision	Related SDG indicators	IMPRESSIONS Indicator selected	Modelled or expert interpretation	Vision indicator target value
Sustainable use of water <i>[adaptation]</i>	Deep aquifers and fossil water are no longer exploited Storm water management, bio-remediation, biologically driven desalination and rainwater harvesting support the sustainable use of water	6.4.2 Level of water stress: freshwater withdrawal as a proportion of available freshwater resources 6.3.2 Proportion of bodies of water with good ambient water quality 6.4.1 Change in water-use efficiency over time 12.2.1 Material footprint, material footprint per capita, and material footprint per GDP	Lack of population-weighted vulnerability to water over-exploitation [% of area]	Modelled	100%
Governance					
New modes of governance <i>[transformative]</i>	- Policy-making in any field is based on scientific evidence (e.g. scientific and finance data), integrated risk assessments - Strong political accountability that avoid externalising negative consequences from unsustainable practices - The population and economy respect the planetary boundaries - Political, financial and individual motives are guided by the protection of Europe's (and the world's) natural resources and environment, as well as cultural heritage - Sustainability is embedded as a fundamental investment criterion in all economic planning	11.3.2 Proportion of cities with a direct participation structure of civil society in urban planning and management that operate regularly and democratically 12.7.1 Number of countries implementing sustainable public procurement policies and action plans 12.8.1 Extent to which (i) global citizenship education and (ii) education for sustainable development (including climate change education) are mainstreamed in 17.14.1 Number of countries with mechanisms in place to enhance policy coherence of sustainable development	Sustainability-focussed multi-level governance	Expert (storyline and pathway text)	Sustainability embedded at all levels (local to international)

Vision element	Text from full Vision	Related SDG indicators	IMPRESSIONS Indicator selected	Modelled or expert interpretation	Vision indicator target value
Environment					
CO ₂ concentration stabilised at 450ppm <i>[mitigation]</i>	The CO ₂ concentration in the atmosphere is stabilized at 450 ppm CO ₂ eq Atmospheric pollution has been cut by 95% compared to the level of 2010	9.4.1 CO ₂ emission per unit of value added 15.1.1 Forest area as a proportion of total land area	Atmospheric CO ₂ concentration	Modelled (climate model output)	450 ppm CO ₂ eq
Balance in preserving and using ecosystem services <i>[adaptation]</i>	Biodiversity is not declining Maintain their integrity and capacity to regulate basic matter, energy and ecological cycles, through a balance in preserving and using ecosystem services	15.1.2 Proportion of important sites for terrestrial and freshwater biodiversity that are covered by protected areas, by ecosystem type 15.2.1 Progress towards sustainable forest management 15.5.1 Red List Index 15.9.1 Progress towards national targets established in accordance with Aichi Biodiversity Target 2 of the Strategic Plan for Biodiversity 2011-2020	Maintain current species extent with climate and habitat space (% of baseline area)	Modelled	100%
Resilience					
Acting pre-emptively <i>[adaptation]</i>	Society is well prepared to adapt to the consequences of climate change in a flexible manner Europeans impacted by climate change are provided with assistance Resilient cities and resilient communities' behaviours are widespread	1.5.1 Number of deaths, missing persons and persons affected by disaster per 100,000 people 1.5.3 Number of countries with national and local disaster risk reduction strategies 11.b.1 Proportion of local governments that adopt and implement local disaster risk reduction strategies in line with the Sendai Framework for Disaster Risk Reduction 2015-2030	Exposed people not vulnerable to flooding <i>[% of exposed population]</i>	Modelled	100%

Table 4.2: Example of draft evaluation of the SSP5 storyline and stakeholders' pathways and actions against the vision element indicator of "Sustainability embedded at all levels (local to international)" (where 10 = Vision met).

Sustainability embedded at levels (local to international)?	Storyline or Pathways	2020s	2050s	2080s
SSP5	<u>Storyline</u>	4/10 (<i>rationale – scenario narrative starting to decline despite investment in innovative technological solutions; top-down</i>) "Global markets are increasingly integrated, with interventions focused on removing institutional barriers to the participation of disadvantaged population groups" "push for economic and social development is coupled with the exploitation of abundant fossil fuel resources" "decrease in political unrest" "stimulates economic wealth, part of which is used to stimulate the development of (green) technologies" "focus on economic growth and export markets rather than environmental policies" "investments in biofuels are low, in favour of cheaper and more readily available fossil fuels"	3/10 (<i>rationale – scenario narrative continuing to decline despite successful innovative technological solutions; top-down</i>) "public trust in political decision-making increases" "Faith is strong in the ability to effectively manage social and ecological systems" "Population across all societal classes ... adopts a very energy intensive lifestyle" "environmental problems are tackled locally and reactively with technological solutions"	2/10 (<i>rationale – scenario narrative continuing to decline</i>) "innovation and a strong focus on technological solutions, with an ever stronger pressure on natural resources" "fuelled by an (over)exploitation of fossil fuel resources" "changed European policy-making, now predominantly focusing on and investing in policies related to human and social capital, rather than environmental protection" "National governments have less political power" "environment is locally seriously degraded"

Sustainability embedded at levels (local to international)?	Storyline or Pathways	2020s	2050s	2080s
	<u>Pathways</u>	<u>5/10</u> (<i>starting to improve some aspects of governance within scenario narrative</i>)	<u>5/10</u> (<i>continued improvement over scenario narrative but no overall improvement from earlier</i>)	<u>6/10</u> (<i>continued elements of environmental improvement over scenario narrative but not embedding SD</i>)
	<u>Pathway 5.1</u>	"Educate young people to achieve higher sustainability"		"Public and private investments are sourced for innovation" "Reward good practices in agriculture (monetary incentives)"
	<u>Pathway 5.2</u>	"Increase government participation and society involvement in economic, social and environmental programs" "Increase participation of decision-making to research and knowledge processes"	"Change the indicators of prosperity to include human development"	
	<u>Pathway 5.3</u>	"Increase agriculture sector awareness on land degradation e.g. profit losses" "Revise of CAP measures" "Regulate to create an environmental market (eco-market)"	"Introduce enabling policies for citizens' actions for environmental restoration" "Strengthen the role of agriculture in integrated planning approaches (cross-sectoral)" "Introduce full cost pricing of degradation in agriculture"	"Create consistent integrated European policies to counter environmental degradation" "Incorporate payment for ecosystem services of agriculture" "Achieve a multifunctional environmental friendly agriculture sector" "Position Europe as a global leader in environmental friendly agriculture"
	<u>Pathway 5.4</u>	"Invest heavily in restoring ecosystems and their services" "Include/integrate value of ecosystem services in economic decisions to select what can work in management for land"	"Introduce higher taxes for fossil fuels" "Use economic power to invest in alternative energy technologies"	"Capitalize on ecosystem services to improve quality of life"
	<u>Pathway 5.5</u>	"Invest in effective and efficient water technologies" "Strong awareness campaign about water"	"Manage the water cycle EU Wide"	

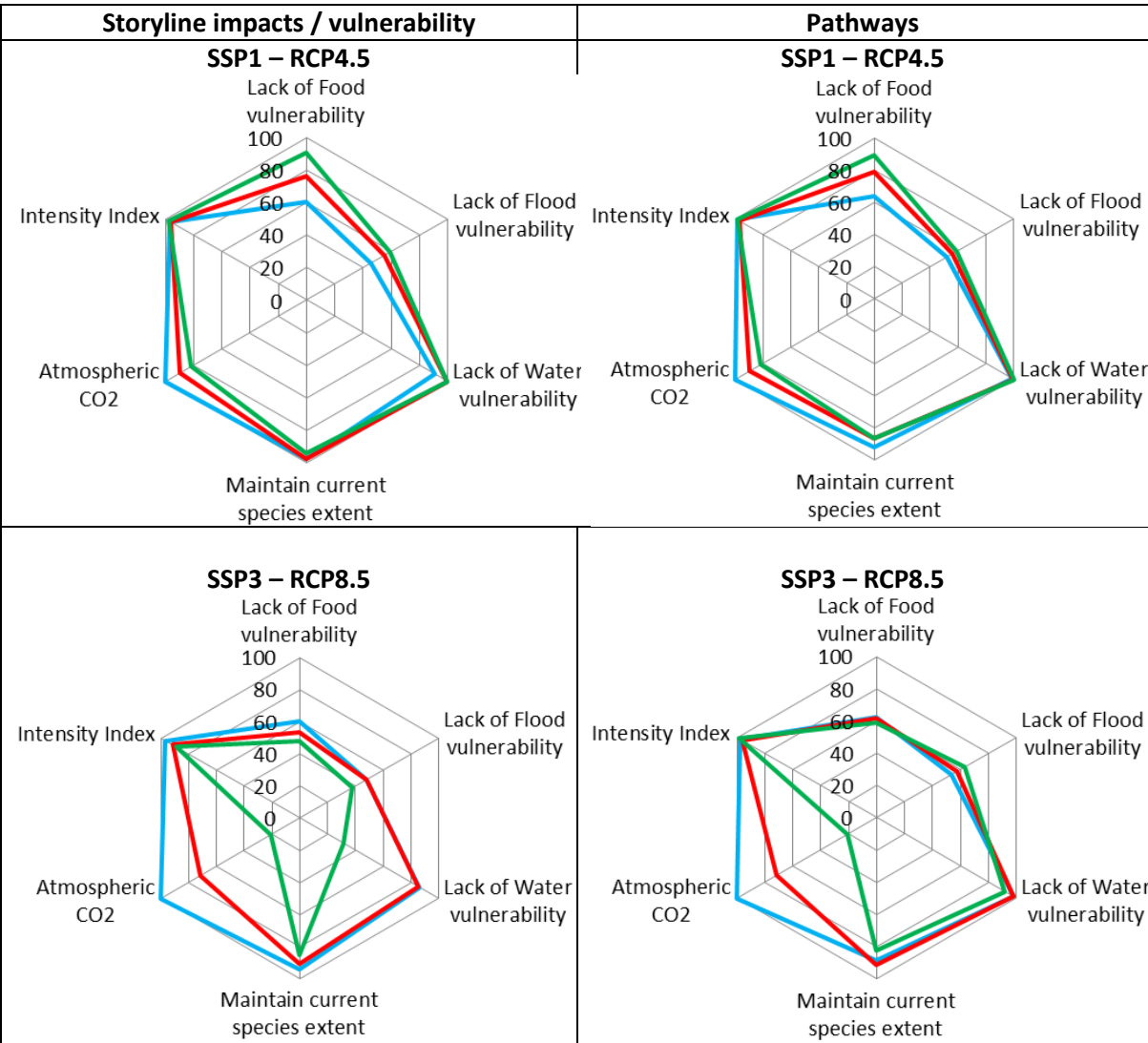


Figure 4.1: Draft preliminary modelled assessment of the impacts / vulnerability on the vision element indicators under the SSP1 x RCP4.5 and SSP3 x RCP8.5 futures and the combined consequences of actions within the pathways [100 = target value] [Blue = 2020s, red = 2050s and green =2080s].

5. Discussion

This deliverable has presented a broad range of modelling outputs from the European case study that cover different model types (agent-based models, physically-based models, meta-models), modelling approaches (scenario-neutral impact response surfaces vs scenario simulations) and system representation (sectoral models vs integrated modelling platforms). Modeling and analysis in the European case study is ongoing and will also contribute to Deliverable D3.2 (Comparison of modelling results across scales) later in 2017.

Whilst there is uncertainty between the individual results from these different approaches, they show that high-end climate change will lead to significant impacts and vulnerabilities in Europe, but also strong spatial differences that provide opportunities in some regions. It is also clear, however, that the differences due to future socio-economic change are as large, or even larger, than those directly due to climate change, thus indicating the potential for European society to exert a strong positive or negative influence on Europe (and the rest of the world).

5.1. Climate model uncertainty

The utility of the simulated changes have to be interpreted in the light of the many sources of uncertainty which are inevitable in any CCIAB study. The regional and global climate model combinations selected by Kok et al. (2015) (Deliverable 2.1) and described in detail in Madsen et al. (2016) (Deliverable D2.3) were selected to span a broad range of changes in global mean temperature from approximately 2°C to more than 4°C and significant differences in spatial and temporal precipitation patterns. As previously mentioned, these were augmented to include RCP2.6 scenarios to encompass global mean temperatures of around 1.5°C. The strong non-linearity in the responses of the impact models to changes in temperature and precipitation evident in the Impact Response Surfaces suggest that many of the simulated impact indicators are likely to be sensitive to the changing magnitude and spatial differences in projected climate change between the different climate models. This is borne out in the European case study, where climate model uncertainty leads to:

- Differential impacts on the productivity of land across Europe due to changes in temperature and soil moisture stress. This leads to differences in the area of land needed to meet European demand for food and timber (Figure 5.1) and its distribution across Europe (Figure 5.2);
- Changes in the hydrological behaviour of river basins as a consequence of changes in the temporal inter-relationships between precipitation, temperature and evapotranspiration. For example, changes in the magnitude and timing of spring snowmelt in the Dvina river (Figure 5.3a); the timing of the return to field capacity and the magnitude of excess rainfall in the autumn in the Danube (Figure 5.3b) and uncertainty in the magnitude of the difference between rainfall and evapotranspiration throughout the year in the Tagus (Figure 5.3c).

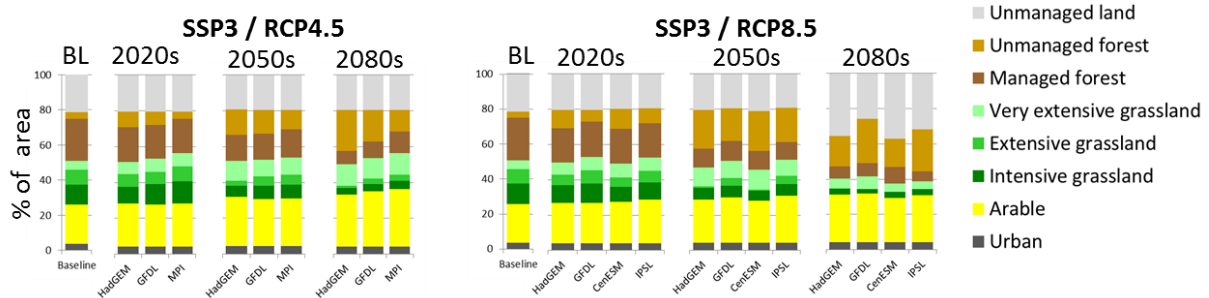


Figure 5.1: The effects on climate model uncertainty on simulated European land use by IAP2 for SSP3 under RCP4.5 and RCP8.5 climates [x-axis labels refer to the Global Climate Model only].

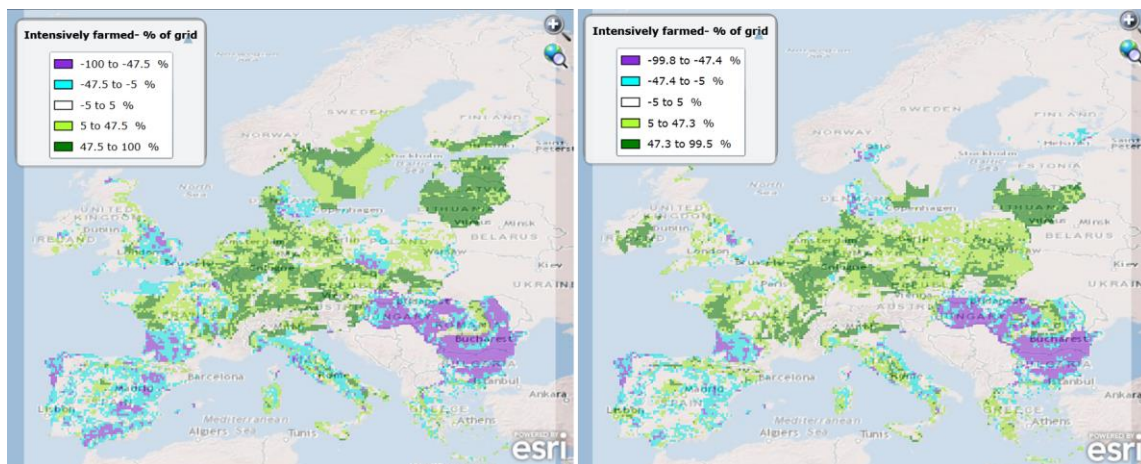


Figure 5.2: Differences in the distribution of IAP2 intensively farmed agriculture in the 2080s under SSP3 x RCP8.5 using climate data from (left) HadGEM2-ES & RCA4 and (right) GFDL-ESM2M & RCA4.

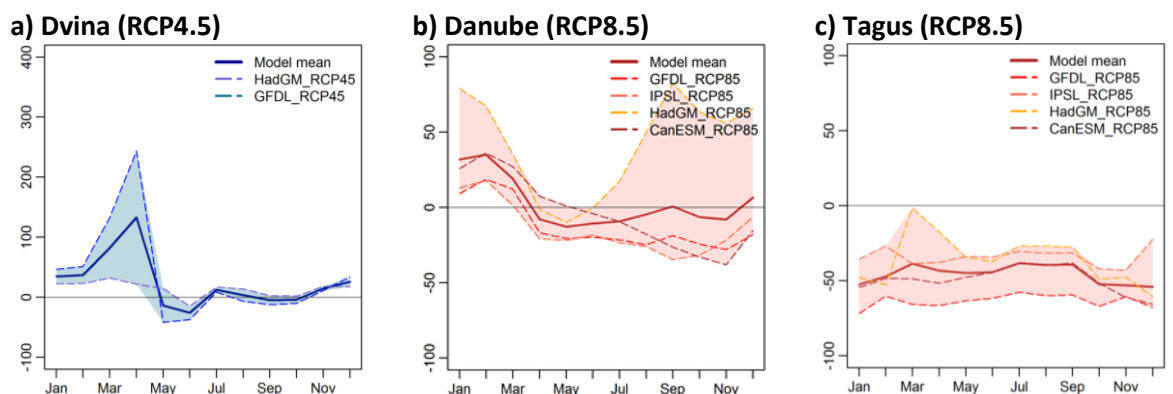


Figure 5.3: Uncertainty in the change (%) from baseline) in selected average monthly river flows simulated by SWIM.

5.2. Impact model uncertainty

5.2.1. Comparison of a detailed model with its meta-model: ForClim vs Meta-ForClim

To assess the consequences of using Meta-ForClim instead of ForClim to predict forest productivity within the European case study, a comparison of the projections made by the two models for five tree species was conducted for 2,500 different grid cells covering Europe (Figure 5.4). This shows that the

absolute differences in predicted forest productivity were quite moderate with average differences at the European scale of less than $\pm 1 \text{ m}^3.\text{ha}^{-1}.\text{year}^{-1}$ for all species, with a tendency of the meta-model to overestimate slightly productivity. At an individual grid cell level, there are both negative and positive differences between the two models of up to ± 3 or $4 \text{ m}^3.\text{ha}^{-1}.\text{year}^{-1}$ for Scots pine (Figure 5.4c), Holm oak and Sessile oak, and slightly higher for European beech and Norway spruce (Figure 5.4f). It is apparent therefore that there is little loss of information from moving to a meta-modeling approach at the European scale.

However, it is also evident from the differences between the outputs of the two models that there are spatial patterns in the differences for some species (Figure 5.4). For Scots pine (Figure 5.4c), Meta-ForClim's predictions match ForClim's in most of Europe, with locally some over- or under-estimation in Southern Europe and a tendency to underestimate productivity in areas of Northern and Eastern Europe. In contrast, Meta-ForClim tends to predict a lower productivity for Norway spruce (Figure 5.4f) than ForClim in areas with abundant precipitation (e.g. British islands, Norway and mountainous areas or Central Europe) and a higher productivity in other part of Europe. Similarly (but not as strongly as for spruce), the productivity of Sessile oak and European beech predicted by Meta-ForClim is lower in the mountainous areas of Central Europe, where the productivity predicted by ForClim is rather high, as well as in some areas in Northern Europe, where these species are at their current northern limit. No clear spatial patterns were detected for Holm oak, only a lower productivity in the south of the British islands (-2 to $-3 \text{ m}^3.\text{ha}^{-1}.\text{year}^{-1}$), where ForClim's predictions tended to be rather high (above $5 \text{ m}^3.\text{ha}^{-1}.\text{year}^{-1}$).

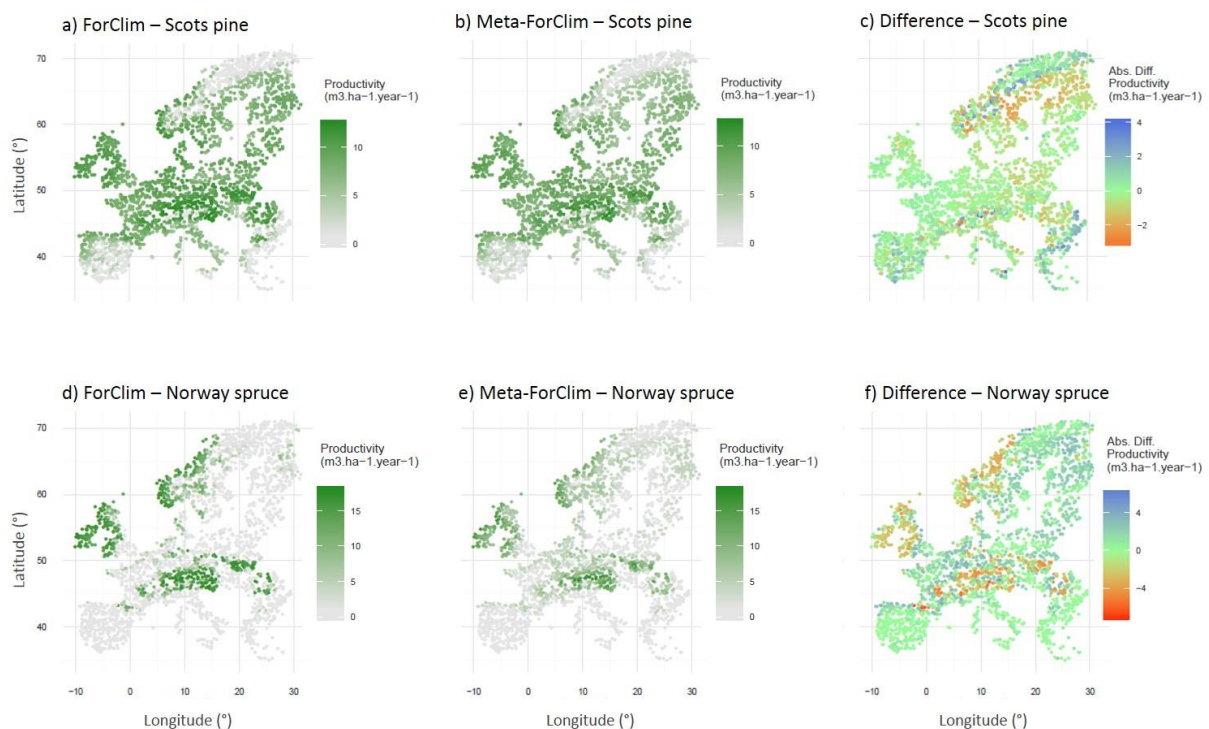


Figure 5.4: Comparison of the forest productivity predicted by ForClim and Meta-ForClim for two tree species in Europe. Results are shown for Scots pine (a to c) and Norway spruce (d to f), for a rather good soil (available water content of 15cm).

It therefore seems that Meta-ForClim predicts lower productivity levels than ForClim in areas with abundant precipitation and higher productivity levels in drier and/or colder areas where ForClim predicts a low or even null growth. This reflects ForClim's high sensitivity to variations in precipitation (as seen in the Impact Response Surface figure - Figure 3.10) where it predicts rather high productivity levels in wet areas and, by contrast, very low productivity levels in dry parts of Europe. However, the regression approach used for the development of Meta-ForClim, which smoothed the response of tree productivity to variations in climatic variables (especially for drought sensitive species like Norway spruce, as seen in the comparison of Figure 5.4d and e) has led to less spatially contrasted variations in productivity levels across Europe that are considered to be more consistent with expert knowledge regarding the expected distribution and productivity of tree species in Europe than ForClim.

5.2.2. Comparison of hydrological modelling results from SWIM and WGMM

The change in water availability calculated by WGMM for the Danube, Rhine and Tagus have been compared with the results from the SWIM model in order to test the reliability of the simple modelling approach in WGMM. The remaining four basins modelled by SWIM are either outside the spatial domain (North Dvina) or are modelled as part of a larger hydrological unit in WGMM. A scatter plot showing the relationship of changes in long-term average river discharge from both models shows acceptable to good agreement (Tagus: $R^2=0.66$, Rhine: $R^2=0.76$, Danube: $R^2=0.77$) (Figure).

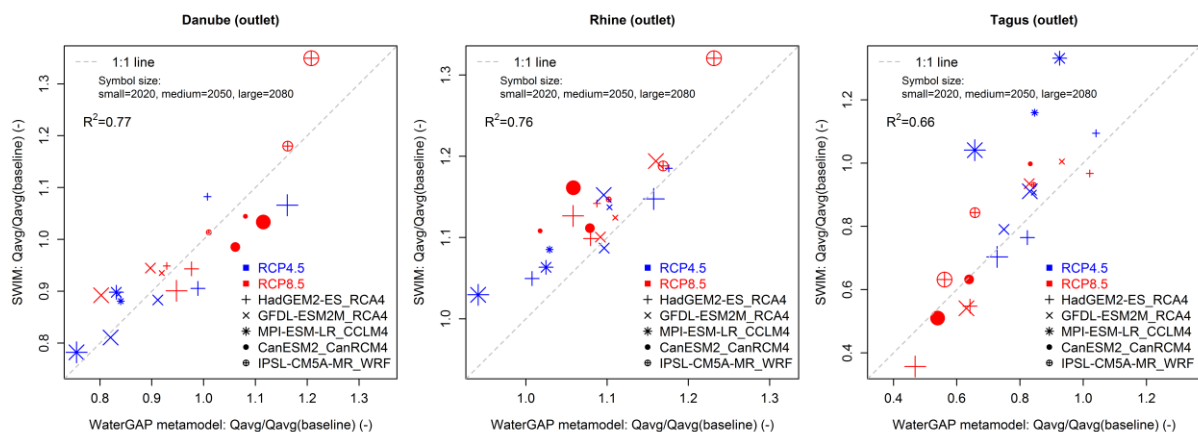


Figure 5.5: Scatter plot of change in average river discharge modelled by SWIM vs WGMM for the Danube, Rhine and Tagus river. The data in the plot covers all available climate projections (GCM-RCM identified by symbol) based on RCP4.5 (identified by blue color) and RCP8.5 (red color) for the periods 2011-2040 (2020s), 2041-2070 (2050s) and 2071-2100 (2080s) (period identified by symbol size).

As individual climate projections can be identified in Figure it is possible to quantify the range of changes in river discharge, i.e. water availability, due to climate model uncertainty. The results are summarised in Table . The largest uncertainty due to climate modelling was observed for the Tagus under RCP8.5 while the largest deviations of WGMM compared to SWIM results (up to 41%) were also found for the Tagus River but under RCP4.5.

A comparison of the change in median annual flood discharge (Q_{MED}) showed poorer agreement between WGMM and SWIM (Figure) than for average flow. For the Danube, the correlation between the results is satisfactory ($R^2=0.77$), but WGMM systematically models higher values. The correlation in the cases of the Rhine ($R^2=0.29$) and Tagus ($R^2=0.24$) are rather poor. Estimated changes of Q_{MED}

from WGMM are systematically lower compared to SWIM for the Rhine. For the Tagus, WGMM mainly projects a decrease in Q_{MED} while SWIM shows both increases and decreases (especially under RCP8.5).

Table 5.1: Range of changes in average river discharge calculated by WGMM and SWIM due to climate model uncertainty for RCP4.5 and RCP8.5.

RCP	River	Period	Range of change in Q_{avg} (%) modelled by		Difference (WGMM-SWIM) with highest abs. value (%)
			WGMM	SWIM	
RCP4.5	Danube	2011-2040	-16 ... +1	-12 ... +8	-8
		2041-2070	-17 ... -1	-12 ... -9	+8
		2071-2100	-25 ... +16	-22 ... +7	+10
	Rhine	2011-2040	+3 ... +18	+9 ... +19	-6
		2041-2070	+1 ... +10	+5 ... +9	-4
		2071-2100	-6 ... +16	+3 ... +15	-9
	Tagus	2011-2040	-16 ... +4	-9 ... +16	-31
		2041-2070	-25 ... -7	-24 ... +33	-41
		2071-2100	-34 ... -17	-30 ... +4	-38
RCP8.5	Danube	2011-2040	-8 ... +8	-6 ... +4	+4
		2041-2070	-10 ... +16	-6 ... +18	-5
		2071-2100	-20 ... +21	-11 ... +35	-14
	Rhine	2011-2040	+2 ... +11	+11 ... +15	-9
		2041-2070	+8 ... +17	+10 ... +19	-3
		2071-2100	+6 ... +23	+13 ... +32	-10
	Tagus	2011-2040	-17 ... +2	-7 ... 0	-16
		2041-2070	-36 ... -17	-45 ... -6	-19
		2071-2100	-53 ... -37	-64 ... -37	+11

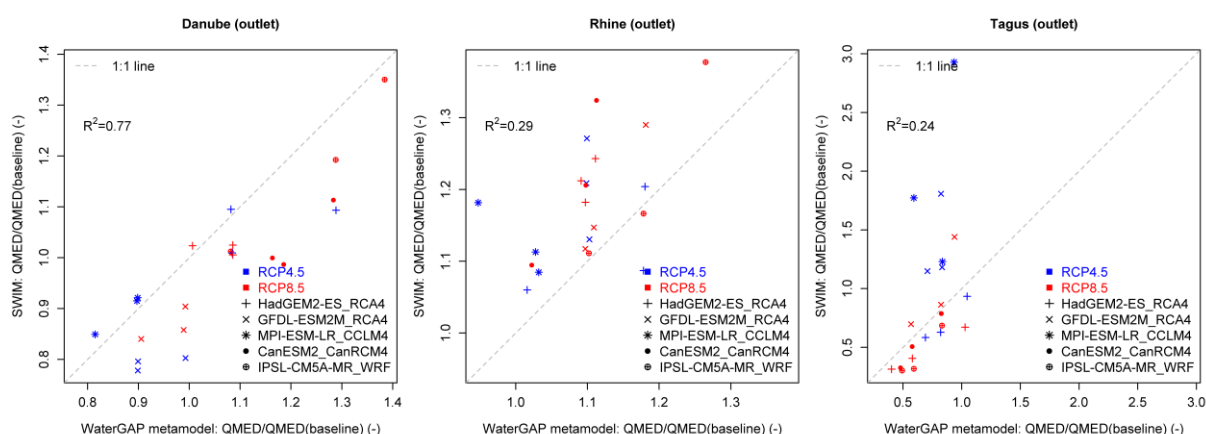


Figure 5.6: Scatter plot of change in median annual flood discharge (Q_{MED}) modelled by SWIM vs WGMM for the Danube, Rhine and Tagus rivers. Symbols as in Figure 5.5.

The relatively good agreement between WGMM and SWIM for Q_{avg} indicates that the simple look-up-table approach in WGMM provides reasonable estimates of changes in average water availability over a wide range of climate conditions. However, a relatively poor agreement was found for Q_{MED} owing to the simple assumption in WGMM that precipitation changes equally through the year according to a constant factor derived as the ratio of long-term mean annual precipitation in the scenario and the baseline period. The consequence of this is especially evident in the Tagus where a decline in mean annual precipitation leads to decreasing Q_{MED} in WGMM but can lead to increased Q_{MED} in SWIM where the reduced average rainfall concentrates in possibly fewer, but more intense, rainfall events causing higher flood discharge.

5.3. Comparison of behavioural and non-behavioural models

The constrained profit-maximising meta-SFARMOD and behavioural agent-based model CRAFTY-EU have clear differences in the way they represent farmer behaviour. These behavioural effects have clear implications for the uncertainty of results, and cause a number of differences between the results of CRAFTY-EU and the IAP2. At the same time, behavioural effects are difficult to calibrate within a widely applied case study, especially under future scenarios, and so the variations described in Table 3.1 do not cause CRAFTY-EU results to deviate from those of the IAP2 in any single, consistent direction. Instead, they illustrate areas of uncertainty that affect both models - depending on the existence and strength of behaviours such as those investigated in CRAFTY-EU, the consequences for land use described in Section 3.1.2 could be expected to occur. A similar consideration is that of climate model uncertainty, which, while less significant than differences in scenarios or behaviours, does have implications for the outputs of both models and erodes the differences between RCP scenarios to some extent.

A more systematic difference arises from the models' treatment of price responses to demand and supply levels. In the IAP2, meta-SFARMOD aims to meet the demand for food (providing there is sufficient available land), assuming that (1) food prices can rise to the level at which agricultural production becomes sufficiently economically viable to fully meet demand and (2) that society can afford to pay that price. This is not the case in CRAFTY-EU, in which variable 'benefit functions' define the response of prices to unmet demand, usually with a finite limit that does not guarantee full production under all circumstances. As a result, intense competition between land uses can occur, and final land use configurations often represent a balance between different shortfalls in supply. This difference is particularly significant in more challenging scenarios such as SSP3, where low productivity levels prompt many agents in CRAFTY-EU to abandon land or de-intensify production, while their IAP2 counterparts continue production due to high price levels. This represents another important area of uncertainty; one which depends on the extent to which future societies would be able to provide sufficient financial support to enable required levels of production (and the relative importance placed on different goods and services). The contrasting assumptions in CRAFTY-EU and the IAP2 represent two clear alternatives, but a (sometimes quite wide) range of possibilities lies between the two.

Notwithstanding these important sources of uncertainty underlying land use projections, there are substantial areas of agreement between the models, suggesting changes that may be particularly likely to occur. These include a tendency for abandonment to occur in particularly marginal (often mountainous) areas, where extensive forms of land use are vulnerable to changes in productivity or economic capital. Similarly, both models suggest that intensive food production will retrench to the most fertile areas of Europe under challenging conditions, with uncertainty concentrated in areas of intermediate productivity. Finally, both show evidence of a polarisation in intensity under high-end climate scenarios, with a decline in the extent of multifunctional production and an increase in specialisation.

5.4. Modelling mitigation pathways

The work presented in this Deliverable has focused on impacts, adaptation and vulnerability. However, work is ongoing within WP5 to use a family of agent based and network models (composed of a set of three computational models) to integrate the simulation of the implementation of mitigation policies into the European case study (see Deliverable D5.2). From a structural perspective these models offer an alternative viewpoint with respect to traditional, computable general equilibrium Integrated Assessment Models for the analysis of coupled climate-economic dynamics and transitions towards greener production systems and they provide complementary tools and information sources. By their very nature, they produce non-smooth growth patterns resulting from disequilibrium interactions among heterogeneous and boundedly-rational agents. This contrasts with the optimal growth trajectories provided by standard models. The presence of endogenous crises is pervasive and can influence the economy's development path and the very process of climate change. For example, crises might favor the relative competitiveness of certain technologies, the final emergence of new paradigms and, in turn, transition towards a greener economy. Moreover, agent-based models provide alternative perspectives on the climate-economy nexus. Green transition can be studied looking at the dynamics of technology adoption at the micro level and across multiple sectors. The links between firms' behavior, financing sources, consumer preferences and the aggregate performance of the economy are naturally embedded in the models' structure. Furthermore, agent-based integrated assessment models allow disaggregated climate and weather shocks and, therefore, avoid the aggregation problems faced in traditional modeling frameworks. Such a feature makes it possible to disentangle the effects of different kind of climate shocks, ranging from capital or inventories destruction to labour productivity losses and energy efficiency deterioration.

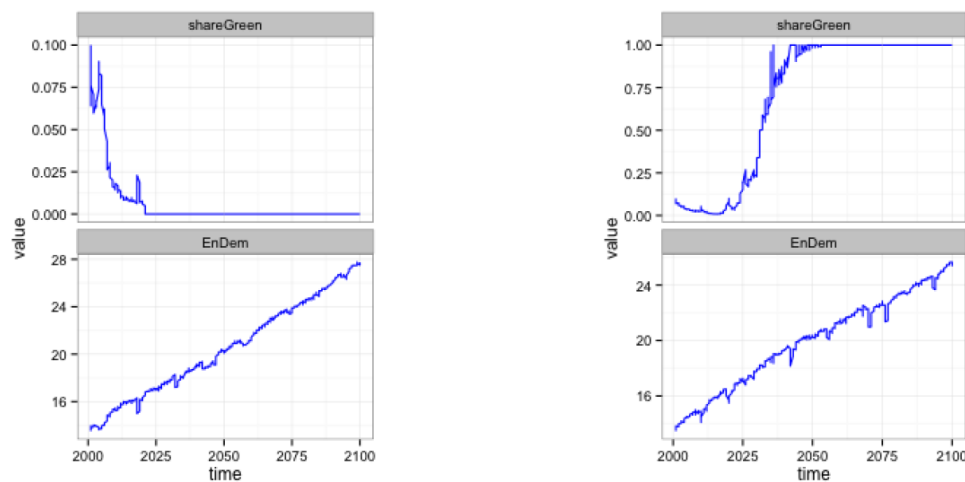
From a practical perspective these models are not meant to be calibrated on a particular economy. Rather their parameters can be fine-tuned in order to replicate (indirectly calibrate) some of the main features of different economic systems. Performing this operation for the European case study allows the impact of different mitigation policies on a variety of outcomes and within different scenarios to be qualitatively assessed. Thus, the models can analyse the likelihood of transitions towards a renewable energy system and how the dynamics towards such transitions may take place. Furthermore, they can simulate how transitions are affected by climate damages and inequality. Finally, they can be used to assess how different policies impact the likelihood of transitions to a green economy and, eventually, the underlying economic dynamics. In particular, the models will be linked to the Eur-SSPs in the following ways:

- SSP1: The models will focus on energy-efficiency and possible trajectories of technological change affecting this dimension.
- SSP4: The models will focus on the introduction and diffusion of green technologies, both in the industrial and energy sectors. Moreover, experiments on the initial level of functional inequality in the economy can be included to better explore the link between this aspect and the pace of green technological advancement.
- SSP5: The models will focus on the introduction of carbon taxes/carbon pricing at different points in time, letting policy interventions interact with path-dependency in the socio-economic dynamics.
- SSP 3: The application of the climate-economy models to this SSP is more difficult and will be further explored. On one hand, the models might be able to account for the severity of climate extreme events and the level of inequality in the economic system while, on the other hand, they are not fully equipped to characterise the circular-economy structure.

Figure 5.7 shows example results from the WP5 models on the share of total energy production obtained through renewable energy sources and the underlying energy demand. Panel (a) provides a

graphical representation of a lock-in in the use of fossil fuel technologies with a resultant decline of green energy while panel (b) shows a typical case of (early) transition in the energy system to a complete reliance on renewable energy sources.

Preliminary, model experiments point to a wide spectrum of results (see D5.2). First, transitions to renewable energy technologies are found to be unlikely without strong policy interventions. Moreover, their timing is crucial; only by moving the whole production of energy from fossil-fuel oriented to green technologies before 2025 would it be possible to keep the global temperature anomaly below the 2°C target with reasonable confidence. Furthermore, simulations of price-oriented policy interventions aimed at inducing the green transition show a non-linear effect that highlight that mild fossil fuel taxes are generally ineffective. Alternatively, price-support policies, such as feed in tariffs for renewable energy technologies, produce an ambiguous effect on aggregate economic growth, with the final positive or negative impact depending upon specific features of the industry. In addition, the simulations show that both policy effectiveness and the likelihood of transitions depend on how climate damages affect individual economic agents. This result is amplified when extreme climate events are taken into account.



(a) Carbon intensive energy technology lock in.

(b) Transition to renewable energy technology.

Figure 5.7: Example results of changes in the energy system showing (a) simulated lock-in in the use of fossil fuel technologies and (b) a typical case of (early) transition to renewable energy reliance.

6. Conclusions

This deliverable describes the broad range of modelling approaches and outcomes within the European case study that have brought together work from WPs 1, 2, 3, 4 and 5. These range from detailed process-based models to behavioural models to meta-models, and from scenario-neutral impact response surfaces to integrated climate and socio-economic scenarios. The IMPRESSIONS case study has advanced the understanding of CCIAB within high end scenarios, with the results demonstrating the significant impacts and vulnerabilities that are likely from high-end scenarios but also some of the opportunities afforded through adaptation, mitigation and transformation. These impacts and vulnerabilities have been shown to be spatially and temporally variable across the diverse European continent, demonstrating the current and future challenges of developing adaptation, mitigation and transformation pathways that can reduce the impacts across Europe and exploit the opportunities. The case study will contribute to the forthcoming European stakeholder workshop where the ongoing pathways analysis will be enriched by Stakeholders in thinking further about how responses at all levels within society can contribute to achieving the stakeholders' Vision for Europe.

7. Acknowledgements

The authors would like to thank colleagues of the IMPRESSIONS project who contributed to the analysis presented in this report through discussions and presentations at five modelling workshops held in London (April 2014), Pisa (September/October 2014), Cranfield (March 2015), Copenhagen (December 2015) and Pisa (November 2016) as well as at General Assembly sessions in Oxford (January 2014), Barcelona (January 2015), Florence (January 2016) and Budapest (January 2017).

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Annex 1: European land use

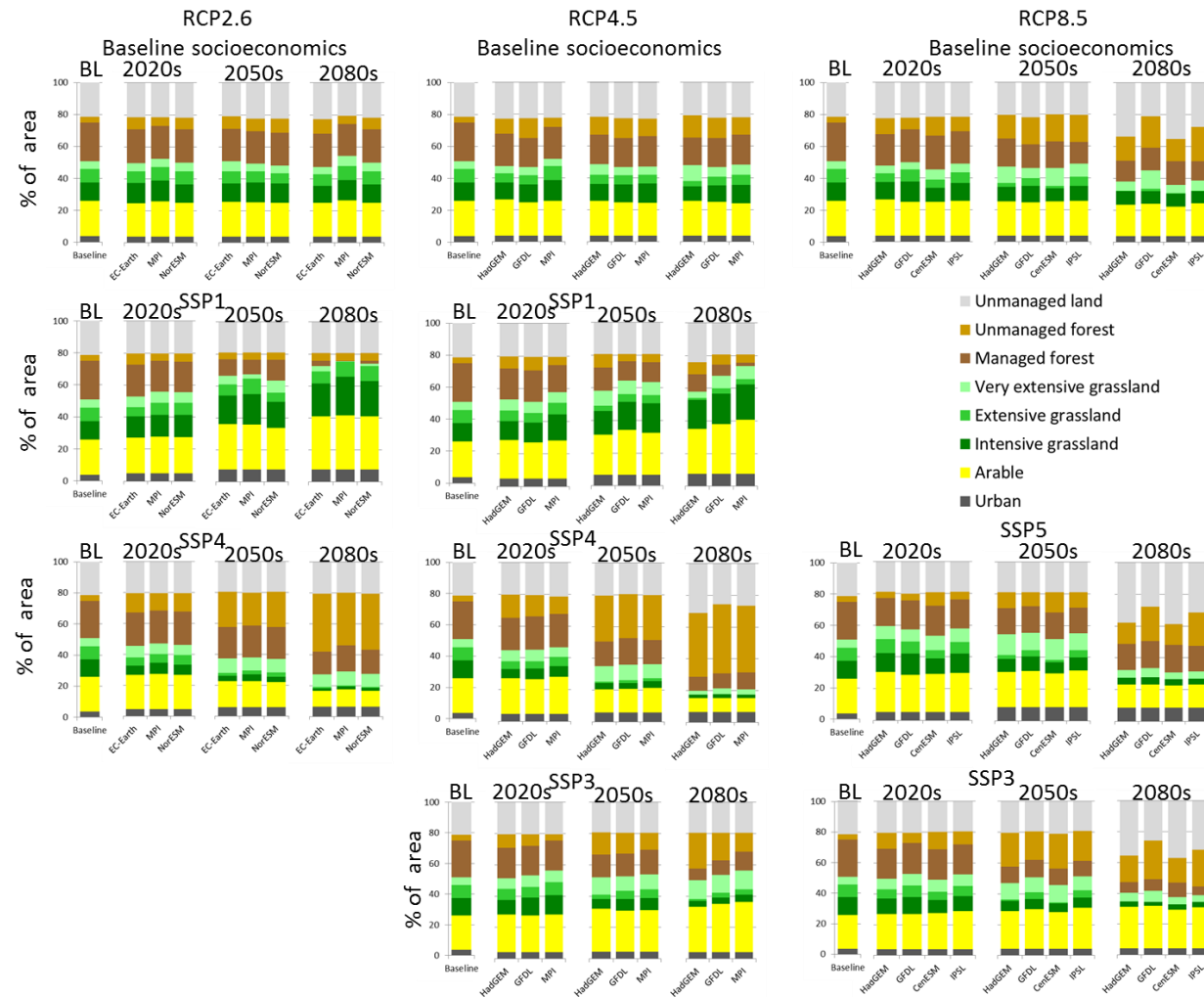


Figure A1.1: Simulated IAP2 European land use for multiple combinations of socio-economic scenario, climate scenario and GCM-RCM climate model [x-axis labels refer to the Global Climate Model only].

Annex 2: SWIM hydrological model results

Table A2.1: Major characteristics of the river basins simulated using SWIM.

Name	Location	Catchment Area, km ²	Length, km	Mean discharge, m ³ /s	Anthropogenic function	Anthropogenic alterations considered in SWIM
Tagus	Iberian Peninsula	80 000	1000 (approx.)	500	Hydropower production, agricultural activities, water supply	Yes, 16 largest reservoirs and the Tagus-Segura Basin Transfer are included
Tay	Scotland	5 200	188	170	Hydropower production, industrial and public water supply	No
Lule	Sweden	25 000	350	500	Mainly hydropower production	Yes, 5 major reservoirs
Eman	Sweden	4 500	220	30	No	No
Northern Dvina	Russia	350 000	744	3 500	Navigation	No
Rhine	Central Europe	185 000	1 232	2 500	Navigation, irrigation, water supply	No
Danube	Central and Eastern Europe	817 000	2 860	7 000	Irrigation, hydropower production, navigation	No

Table A2.2: The Nash-Sutcliffe efficiency and Relative Volume Error values for the calibration and validation periods for the SWIM model using the monthly time step.

River		Nash Sutcliff Efficiency	Relative Volume Error, %
Northern Dvina	Calibration	0.93	-3.15
	Validation	0.95	-8
Emon	Calibration	0.86	8.6
	Validation	0.78	-9.5
Rhine	Calibration	0.69	-0.12
	Validation	0.52	-0.13
Tay	Calibration	0.85	1.6
	Validation	0.88	1
Tagus	Calibration	0.82	15
	Validation	0.81	-12
Danube	Calibration	0.86	-4.6
	Validation	0.87	-5.9
Lule (naturalized flow)	Calibration	0.69	-0.9
	Validation	0.62	-0.3

Table A2.3: Combinations of socio-economic scenarios, climate scenarios and climate model output used as input to WGMM, CFFLOOD or SWIM as addressed by modelling results shown in the section.

		Climate scenarios		
		RCP2.6	RCP4.5	RCP8.5
Socio-economic scenarios	SSP1	WGMM: EC-EARTH_RCA4	WGMM: HadGEM2-ES_RCA4	WGMM & CFFLOOD: HadGEM2-ES_RCA4
	SSP3		WGMM: HadGEM2-ES_RCA4	WGMM: HadGEM2-ES_RCA4 CFFLOOD: HadGEM2-ES_RCA4 IPSL-CM5A-MR_WRF
	SSP4	WGMM & CFFLOOD: EC-EARTH_RCA4	WGMM & CFFLOOD: HadGEM2-ES_RCA4	
	SSP5			WGMM & CFFLOOD: HadGEM2-ES_RCA4
	None		WGMM & SWIM: HadGEM2-ES_RCA4 MPI-ESM-LR_CCLM4 GFDL-ESM2M_RCA4	WGMM & SWIM: HadGEM2-ES_RCA4 CanESM2_CanRCM4 IPSL-CM5A-MR_WRF GFDL-ESM2M_RCA4

Calibration and validation results for the SWIM simulations of the case study river basins

Danube

The SWIM model for the Danube was initially setup, calibrated and validated using the WATCH Era 40 dataset. The initial model application is described in Stagl and Hattermann (2015). In IMPRESSIONS, the model was re-calibrated using the WATCH Era Interim dataset. As presented in Figure , the SWIM model was able to represent the long-term mean annual dynamics as well as mean monthly flows of the Danube River. The results on the mean annual flow (50th percentile) and the 90th and 10th percentiles also show a good fit to the observed values.

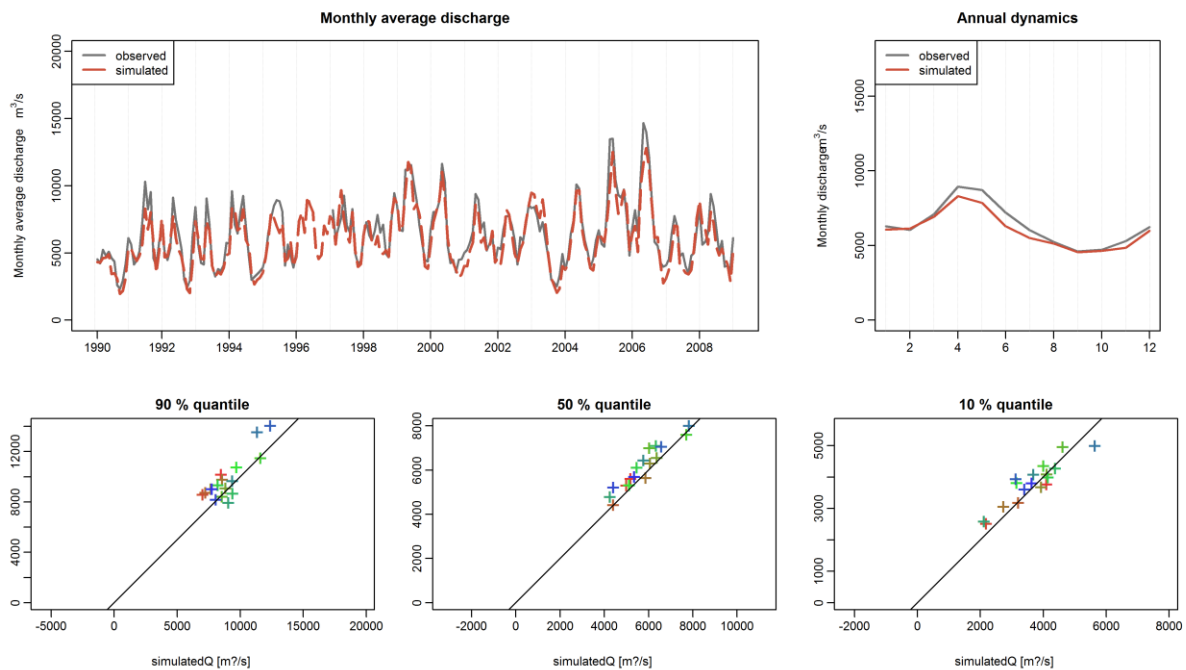


Figure A2.1: Calibration and validation results for the monthly discharge at the Danube River outlet (Ceatal Izmail, top left), long-term mean annual dynamics (top right), and 90th, 50th and 10th flow percentiles (bottom), driven by the WATCH Era Interim climate.

Northern Dvina

The SWIM model showed the best fit between the observed and simulated values of the long-term mean annual dynamics and monthly average flows for the Northern Dvina among all basins under consideration (Figure A2.2). The situation for high flows was different, as the model tended to underestimate the high flows (90th percentile) systematically.

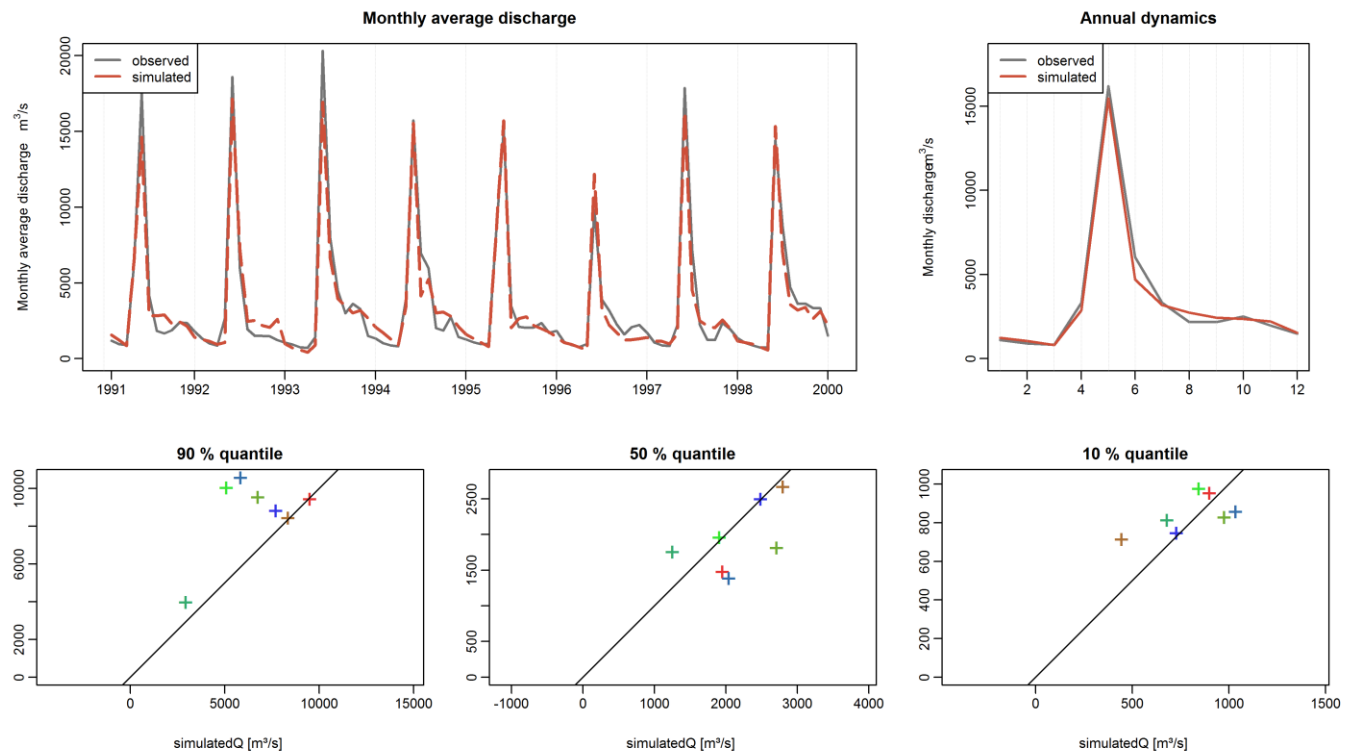


Figure A2.2: Calibration and validation results for the monthly discharge of the Northern Dvina River at the Ust-Pinega station, annual long-term average dynamics and 90th, 50th and 10th flow percentiles, simulated with WATCH Era Interim.

Emon

While the SWIM model was successful in representing the annual dynamics and mean monthly flows (indicated by the high NSE and RVE values) for the Emon basin, the low flows were overestimated by the model during the summer period (Figure).

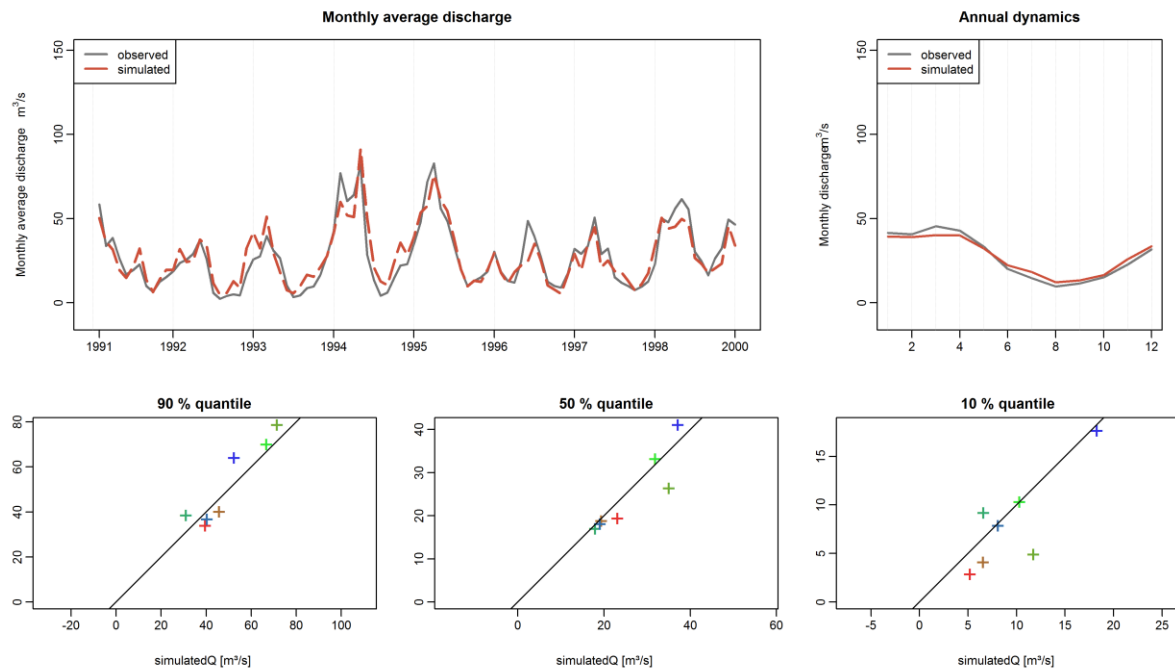


Figure A2.3: Calibration and validation results for the monthly discharge of the Emon River at the Ust-Pinega station, annual long-term average dynamics and 90th, 50th and 10th flow percentiles, simulated with WATCH Era Interim.

Lule

The SWIM model for the Lule River basin includes the four largest reservoirs within the catchment (Suorvadammen, Porjus, Vietas and Seitevare). Generally, the flow of the Lule River is significantly altered by water management. Initially, the SWIM model was calibrated for the naturalised flow of the Lule River, which was obtained from the HYPE model simulation (SMHI). After calibration to the naturalised flow, the four selected reservoirs were included in the SWIM model. As can be seen in Figure , where the simulated values are shown against the real observed discharge of the Lule River, the inclusion of reservoirs improved the performance of the model, and the curve of the outflow approaches the real observed values. However, due to lack of measured data for the reservoirs it was impossible to approximate their management with sufficient accuracy, and the SWIM model could not catch the observed dynamics properly. Nevertheless, after adjustment the model was applied for scenario simulations under climate change.

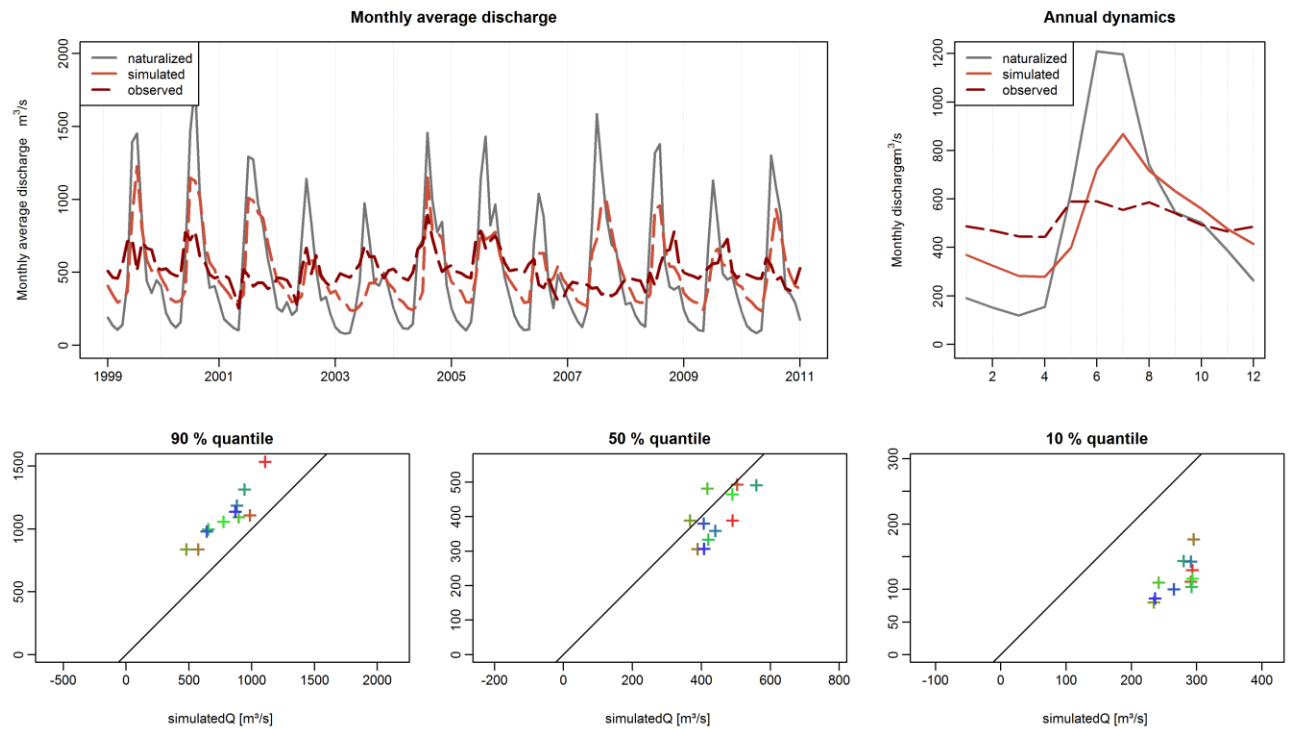


Figure A2.4 Calibration and validation results for the monthly discharge of the Lule River at the Stora Luleälven reservoir outlet, annual long-term average dynamics and 90th, 50th and 10th flow percentiles, simulated with WATCH Era Interim

Rhine

The SWIM model was set up for the Rhine river as described in Huang et al. (2013). Initially, it was calibrated and validated using the WATCH Era40 dataset. For the IMPRESSIONS project the model was re-calibrated using the WATCH Era Interim dataset (similarly to the Danube model). The SWIM model of the Rhine River does not include the dynamics of the lake Constance. Figure presents the calibration and validation results of the SWIM model simulation for the Rhine. As can be seen, the simulated discharge shows a very good fit to the observed dynamics, especially during summer, autumn and early winter months, whereas for late winter and spring the model tends to overestimate river discharge (Figure).

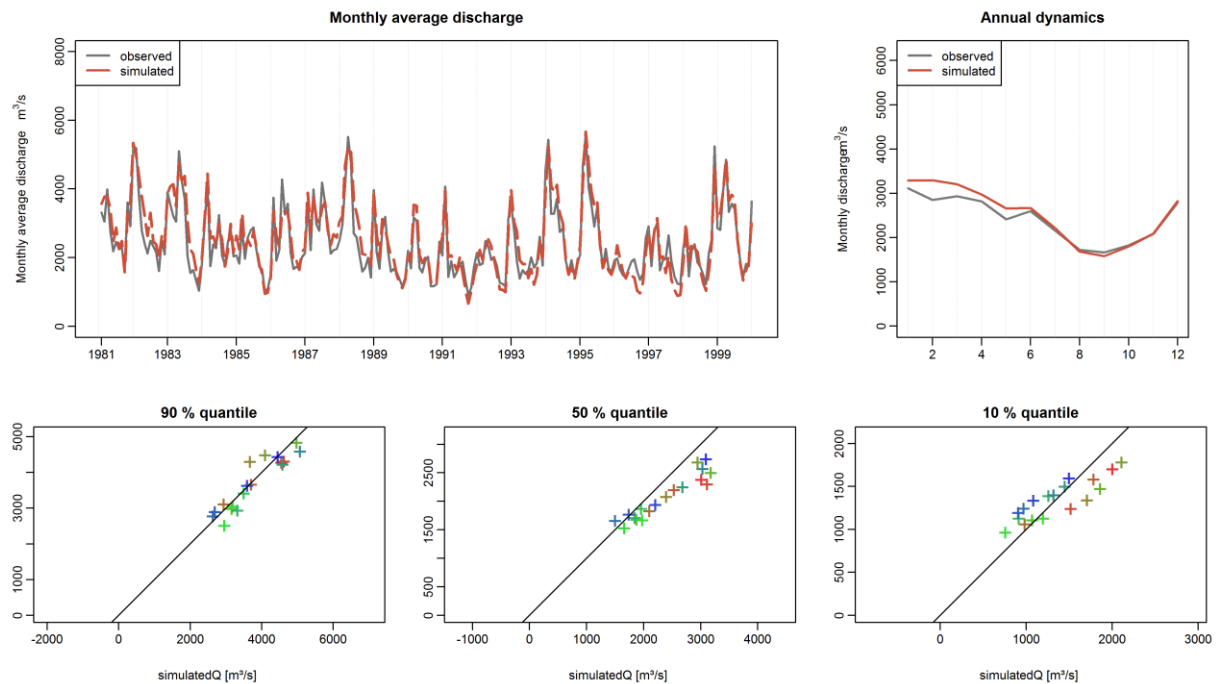


Figure A2.5: Calibration and validation results for the monthly discharge of the Rhine River outlet at Rees station, annual long-term average dynamics and 90th, 50th and 10th flow percentiles, simulated with WATCH Era Interim.

Tay

The SWIM model applied for the Tay River basin did not take into account lakes in the catchment. Some of the natural lakes in the Tay catchment are regulated for production of hydropower. However, data on water inflows and outflows were inaccessible, and therefore the influence of the lakes dynamics on discharge was not taken into account. The observed and simulated discharge time series show a good fit, though the model slightly underestimates flows in winter and early spring, and overestimates them in late summer and autumn months (Figure A2.6). The high flows were simulated quite well, but the low flows (10th percentile) were systematically underestimated by the model.

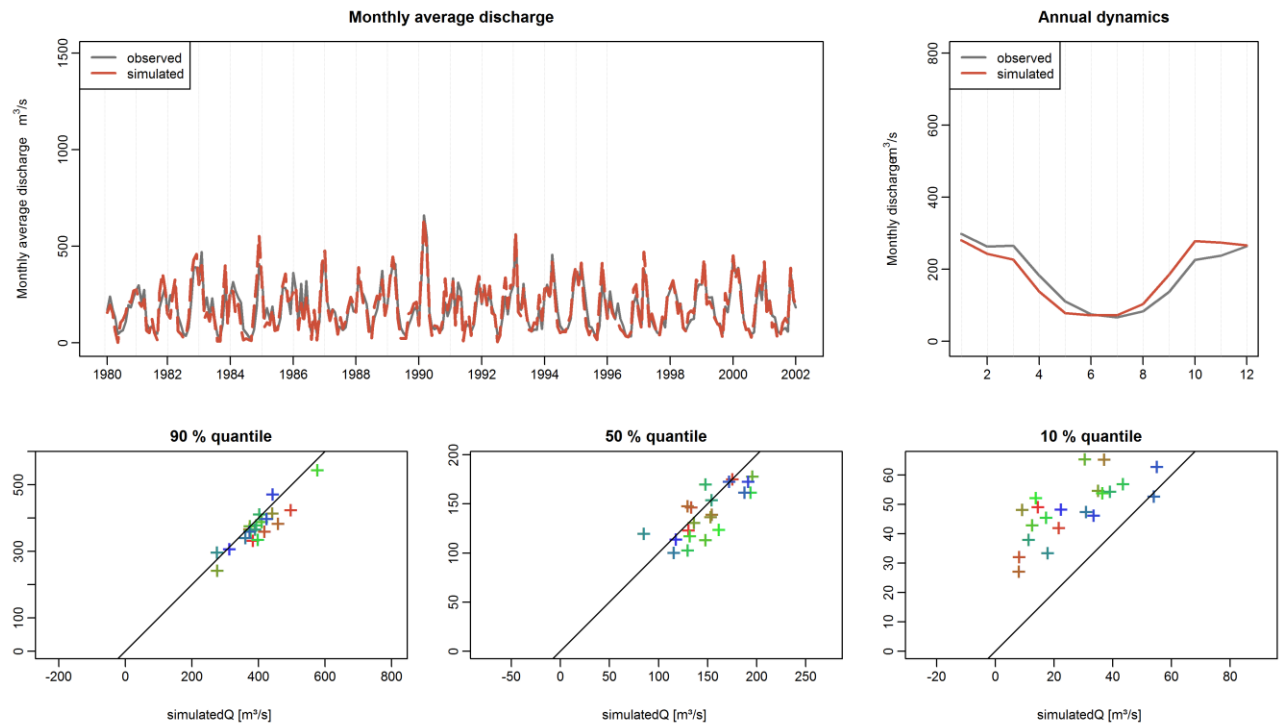


Figure A2.6: Calibration and validation results for the monthly discharge of the Tay River at the outlet, Ballathie station, annual long-term average dynamics and 90th, 50th and 10th flow percentiles, simulated with WATCH Era Interim.

Tagus

The SWIM model for the Tagus River basin includes the 16 largest reservoirs, and the famous inter-basin water transfer, the Tagus Segura Transfer. The dynamics of the Tagus Segura transfer was not included in the simulations of the future scenarios for this case study. However, the possible evolution of the Segura basin demands according to the SSPs described in Deliverable D2.2 was taken into account within the Iberian case study.

The SWIM model was able to capture the dynamics of discharge of the Tagus River, and the simulated mean monthly discharge shows a fairly good fit to the observed values (Figure). However, the low flows, or 10th percentile, show quite a weak comparison with the observed values. This might be due to the management of the reservoirs (not all were included in the model), as well as due to large water withdrawals for irrigation, which take place in summer months.

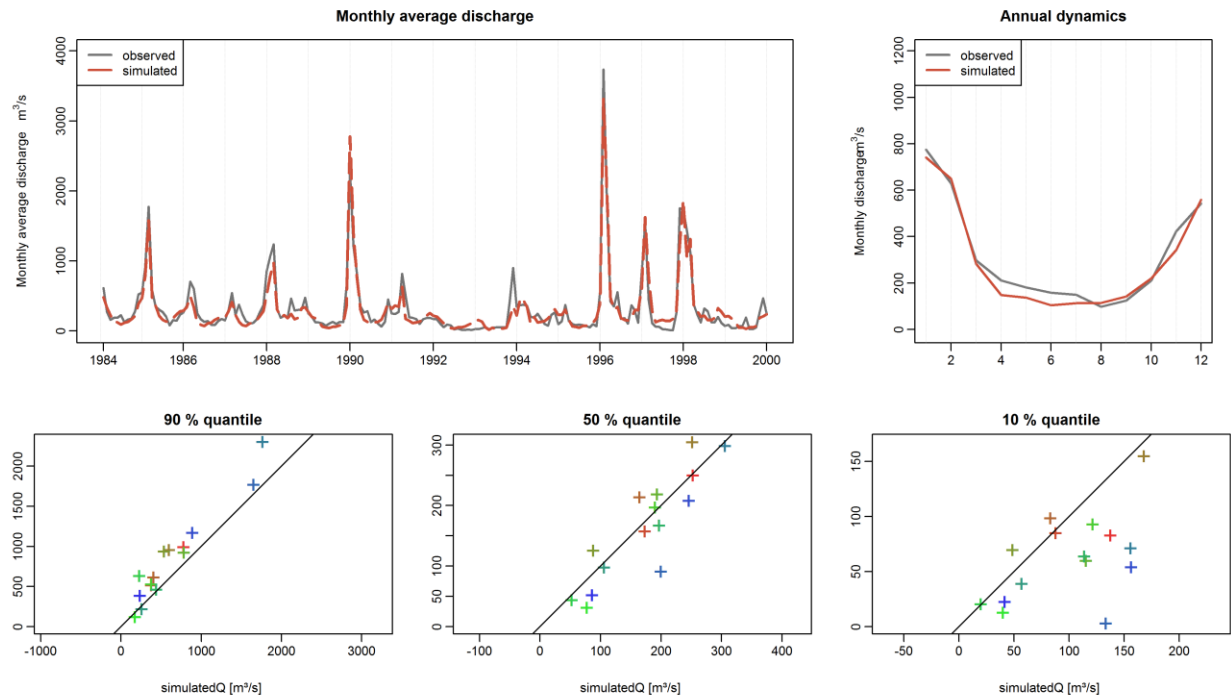


Figure A2.7: Calibration and validation results for the monthly discharge of the Tagus River outlet, Almourol station at the outlet, Almourol station, annual long-term average dynamics and 90th, 50th and 10th flow percentiles, simulated with WATCH Era Interim.