Comparison of modelling results across scales

Deliverable D3.2

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

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Preface

The EU-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 high-end projections of future climate change and operating in the context of alternative socio-economic 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 adaptation 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 compares and analyses the modelling of impacts across scales as part of Task 3.4. Results from the European case study are compared quantitatively and qualitatively to results from the three regional case studies (Scotland, Iberia and Hungary). Results from the Central Asia (EU external) case study are presented independently, but interpreted in terms of indirect effects on Europe.

Summary

This deliverable presents the results of a cross-scale and inter-model comparison and assessment of the wide selection of model applications completed in the IMPRESSIONS project for the different case studies. The analysis is divided into (i) quantitative, inter-model comparisons by sector, (ii) inter-model and cross-scale comparisons using impact response surfaces, and (iii) qualitative synthesis of a range of model output indicators across case studies in tables. The cross-scale comparison is based on the pan-European results, compared to the three regional/local case studies in Scotland, Iberia and Hungary. A further analysis synthesises results from the EU external (EUx) case study of Central Asia using semi-quantitative indicators.

The integrated assessment approach, as outlined in Deliverable D3.1 (Carter et al., 2015), provides the framework for this study. It ensures the inputs/outputs to models were harmonised to the greatest possible extent making a model inter-comparison feasible as well as supporting the integration of models. In addition, the integrated climate and socio-economic scenarios that combine the Representative Concentration Pathways (RCPs) and the Shared Socio-economic Pathways (SSPs) (see Deliverable D2.4 – Kok et al., 2018) linked all of the model applications.

The quantitative inter-model and cross-scale comparisons contain results for the key sectors: agriculture (crop yields); forestry; water; rural land use; and urban land use (including population growth). For most sectors, results from the IMPRESSIONS integrated assessment platform (IAP2) were compared to the outputs from other relevant models. The inter-model comparisons were useful in identifying climate change impacts that agree across models and areas where further research is needed. In addition, using a variety of sectoral models, as well as integrated cross-sectoral models, enables a fuller picture to be created of cross-sectoral interdependencies and provides greater contextual understanding of feedbacks between sectors. The inter-model comparison has shown that impacts under high-end climate change are going to be severe, however, models differ in their estimation of magnitude and sometimes also direction of change. This applies to the land use models, where different modelling assumptions underlying the CRAFTY and the IAP2 models lead to different expected land use impacts. However, these differences, rather than invalidating results, show the need to question underlying model assumptions and continuously research and adjust models to improve outcomes.

The assessment of model sensitivity using Impact Response Surfaces for European sub-regions showed a large variation of sensitivities across individual indicators and regions for most indicators. Exceptions are two river discharge indicators and, to a lesser extent, net primary production and agricultural land use, whose regional values clustered around a small range of sensitivities both for temperature and precipitation. North-eastern Europe showed increases in yields of all crops and basal area of all tree species, whereas Central and Eastern Europe showed decreases in these indicators. In regions of southern Europe (Iberian Peninsula, France and Mediterranean) indicators of river discharge and stem basal area (except Holm oak) were projected to decrease, whereas crop yields increased in these regions, where it was assumed that irrigation would compensate for decreases in precipitation.

The qualitative synthesis of land use indicators (changes in urban area, intensive agriculture, extensive agriculture, pasture area), crop yields (wheat, barley, maize), forestry (managed and unmanaged forest area), water indicators (water availability, water exploitation index, change in people flooded, changes in discharge and flooding for select river systems) and wellbeing indicators (Lyme disease risk, ecosystem services supply/demand gap, heat mortality) showed consistencies in the direction of impacts across case studies for most indicators. However, the magnitude of impacts varies by region. Scotland generally experiences less change than the other regions, with the exception of Lyme disease risk, which increases much more strongly and crop yields, which show beneficial increases across all scenarios. In comparison, Iberia experiences more negative impacts, particularly in the water and

wellbeing sectors. Water availability in Iberia decreases for all climate change scenarios, although water availability averaged across the whole of Europe increases. In addition, heat mortality in the population older than 75 years is projected to increase the most in Iberia.

The work reported here has built on the findings of previous deliverables (Deliverables D3B.2 – Holman et al., 2017 and Deliverable D3C.2 – Clarke et al., 2017) by bringing together the model results from different case studies and presenting a cross-scale and inter-model comparison. This has highlighted important similarities as well as divergences in the direction and magnitude of a variety of climate change impacts. In addition, through inter-model comparisons, it was possible to analyse the assumptions that go into individual models as well as highlighting model uncertainties. This is important as greater knowledge about uncertainties can support stakeholders in making decisions about adaptation measures to address the future impacts of high-end climate change.

1. Introduction

The overall objective of WP3 is to advance and apply multi-scale integrated assessment methods and models to quantify and understand climate change impacts, adaptation and vulnerability (CCIAV) associated with high-end scenarios for key economic, social and environmental sectors and their cross-sectoral interactions.

This Deliverable (D3.2) focuses on the cross-scale and inter-model comparison of a range of CCIAV models. Understanding CCIAV across scales is vital, as climate change impacts are likely to vary across scale, not only in direction, but also in impact. This deliverable therefore compares and synthesises results from the individual IMPRESSIONS case studies (Europe, Hungary, Scotland, Iberia and Central Asia) to highlight commonalities as well as divergences between the cases. Understanding these variations can enable decision-makers to implement spatially and contextually specific adaptation measures that are suitable for a specific socio-economic context.

Inter-model comparisons help uncover model- as well as scenario-related uncertainties. Uncertainty is a factor that needs careful consideration in any modelling exercise, and this is particularly the case for CCIAV modelling, where uncertainties not only exist concerning the individual models used, but also in relation to climate change and socio-economic scenario uncertainties. The inter-model as well as the cross-scale comparisons can therefore help identify uncertainties related to these issues. In addition, by using a variety of models, individual model uncertainties can be mediated by the strengths of other models. A better understanding of uncertainties is important to enable effective decision-making despite gaps in our knowledge.

An overview of the sensitivity analyses that were undertaken for a range of CCIAV models using Impact Response Surfaces (IRS) for European sub-regions is also presented within this deliverable. For an IRS, a sensitivity analysis of a model to systematic changes in key climatic and socio-economic drivers is conducted and the resulting impact variable is plotted as a surface comprising contour lines of equal response. The IRS approach provides an opportunity to test model performance across a wide range of conditions, including those found at the high-end of projected changes that may lie outside the conventional application of many models. The outcomes can then assist in summarising and comparing model behaviour across sectors and regions.

This deliverable compares the climate change impacts that result from applying the integrated assessment approach outlined in Deliverable D3.1 (Carter et al. 2015) across the multiple scales and models of the IMPRESSIONS project. The deliverable is divided into the following parts:

- Section 2 provides background to the integrated scenarios that were used with the CCIAV models and the case study regions.
- Section 3 presents a quantitative inter-model and cross-scale comparison for key sectors (agriculture, water, forestry, land use and urban).
- Section 4 presents an IRS inter-model and cross-scale comparison.
- Section 5 presents a qualitative synthesis of results across case studies and models, summarising and comparing the magnitude and direction of change in key indicators. Synthesis tables are used to visualise projected impacts across the different scenarios and highlight differences between regions.
- Section 6 presents a synthesis of results from the Central Asia (EU External) case study across the key sectors of energy, trade, conflict and security, and migration, and provides an interpretation of the possible indirect implications of such impacts for Europe.

1.1. Description of work

This deliverable is produced in fulfilment of Task 3.4: "Analysis and comparison of the CCIAV results across scales", which the Description of Work sets out to:

> *[…] undertake a comparison of the results from the different methods and models at the multiple scale levels using spatio-temporal windows of model outputs that are common to each level. The global scale modelled results will be compared with the pan-European results for the European window for a limited set of common output variables and for a common set of scenarios. Likewise the European model results will be compared with results for the three regional/local case studies. The inter-comparison will be used to examine the effect of spatial resolution on model outcomes and on the ranges of uncertainty in the assessment models. For example, impact response surfaces offer one technique for investigating the strength and direction of impact responses within and across regions. The effects of scenario resolution will also be analysed. Model results will be compared statistically to evaluate the significance of the differences between the scale levels and to identify particular locations where the models either agree or disagree in direction or magnitude of change.*

As the model applications were selected to match the key challenges in each case study in consultation with local stakeholders, some indicators differ across scales or between case studies, making comparison more challenging in some cases.

1.2. Links to other work packages

Work Package (WP) 3 consists of modelling work from all three IMPRESSIONS scale levels; global (WP3A), European (WP3B) and regional/local (WP3C). More detailed descriptions of model results are presented in Deliverables D3A.1 (Carter et al., 2016), D3B.2 (Holman et al., 2017) and D3C.2 (Clarke et al., 2017). This deliverable builds on the multi-scale modelling framework described in Deliverable D3.1 (Carter et al., 2015). The integrated modelling approach underpinning the majority of the results presented in this deliverable is founded on close linkages with other parts of the IMPRESSIONS project. The scenario development (WP2) and the future visions (WP4/5) have informed the model applications.

2. Methods

The different case studies follow a common methodological framework. This includes case study specific scenarios, which hinder or support climate change adaptation and mitigation actions, a vision for the case study areas in 2100 and case study specific pathways to reach this vision. The global and European case studies provide boundary conditions for the local case studies. Stakeholder workshops played an important role in all case studies. The input of stakeholders was used to develop case study specific scenarios and visions, as well as to identify key climate change adaptation and mitigation actions and sequence them within adaptation, mitigation and transformation pathways. Details of the visions and pathways that were developed for each case study are reported in Deliverable D4.2 (Hölscher et al., 2017).

For the modelling work conducted in IMPRESSIONS, an integrated assessment approach was developed and followed. This was based on the following guiding principles:

- Integration across scales and across sectors supported by the development of data dictionaries to harmonise model inputs/outputs;
- Using the data dictionaries to establish information flows across modelling scales;
- Accommodating scenarios as a starting point (across temporal/spatial scales and sectors);
- Defining what is needed by the models from the scenarios (both qualitative/quantitative);

- Simulating synergies and trade-offs in impacts across sectors and scales;
- Focusing on adaptation (based on limits to adaptation);
- Taking account of time dependencies in impacts and adaptation;
- Simulating the adaptation, mitigation and transformative solutions within the pathways as much as feasible;
- Synthesising and communicating model outputs to stakeholders.

To achieve these ambitions, the integrated approach is implemented through the following steps that address key research and policy-related questions defined jointly by researchers and stakeholders for each case study:

1. A conceptual framework based on a revised Driver-Pressure-State-Impact-Response (DPSIR) framework;
2. A modelling framework that identifies the relationships between the different models used in each case study, as well as the relationships across geographic scales;
3. A set of modelling protocols that guide the various model applications within each case study.

A full description of the integrated assessment approach is presented in Deliverable D3.1 (Carter et al., 2015), and a table of the models used for all the analysis in the IMPRESSIONS project is provided in the Annex to this deliverable (Table A1).

The specific methods used for the analysis in this deliverable are laid out in each individual section (Sections 3-6). A background to the scenarios and case studies that have informed the modelling in IMPRESSIONS is given below.

2.1. Climate and socio-economic scenarios

The selected scenarios were based on the RCP x SSP scenario framework and serve as the basis for the modelling runs at different scales (see Deliverable D2.1; Kok et al., 2015 for a detailed description of the selection of climate and socio-economic scenarios for the project). Representative Concentration Pathways (RCP) 4.5 and 8.5 were chosen as they cover moderate as well as high-end climate change scenarios and go beyond the 2°C threshold set by the Paris Agreement at a global level. An additional set of low-end climate change scenarios (RCP2.6) were added for the European case study after the initial scenario selection to respond to a request from the European Commission after the Paris Agreement in December 2015. Four Shared Socio-economic Pathways (SSPs) were chosen, covering a diverse range of plausible future socio-economic conditions: SSP1, SSP3, SSP4 and SSP5. The RCPs and SSPs were combined by linking the SSP narratives to the likely climate change outcomes resulting in four integrated scenarios that represent high and low mitigation and adaptation challenges. The five integrated scenarios were:

- SSP1 x RCP4.5
- SSP3 x RCP4.5
- SSP3 x RCP8.5
- SSP4 x RCP4.5
- SSP5 x RCP8.5

The scenarios were downscaled and further developed through a stakeholder-led process. This process focused on four of the five scenarios for pragmatic reasons (excluding SSP3 x RCP4.5). This resulted in context specific scenarios for each case study. See Deliverables D2.2 (Kok & Pedde, 2016) and D2.3 (Madsen et al., 2016) for full overviews of the socio-economic and climate scenarios for each case study, respectively, and D2.4 (Kok et al., 2018) for the cross-scale analysis of the integrated climate and socio-economic scenarios.

2.2. Description of case studies at different scales

A short overview is provided of the aims of each case studies and the models that were selected for application within the case study. This provides the necessary background to understand the inter-model and cross-scale comparisons provided in the next section.

2.2.1. Europe

The European case study was designed to advance and improve climate change impact and adaptation modelling across Europe. The case study area covers the area of EU member states as well as Norway and Switzerland, but excludes Cyprus. It employed a variety of CCIAV models to explore climate change impacts for land use, water, forestry and human wellbeing sectors with input from global and European scale datasets.

Models used:

- Integrated models: European Integrated Assessment Platform 2 (IAP2), regional Integrated Assessment Model (rIAM) (multiple land and water sectors);
- Physically-based model: SWIM (hydrology);
- Statistical model: HEET (Heat stress mortality);
- Agent-based model: CRAFTY (land use change).

For a full description, see Deliverables D3B.1 (Holman et al., 2015) and D3B.2 (Holman et al., 2017).

2.2.2. Scotland

The Scottish case study analysed impacts of climate change at the national scale. It focused on risks posed by high-end scenarios to land and water resource sectors, including agriculture, forestry, tourism, health and river flows.

Models used:

- Integrated model: Scottish IAP2 (multiple land and water sectors);
- Physically-based model: SWIM (hydrology);
- Agent-based model: LYR model (Lyme disease);
- Physically-based model: ForClim (forest productivity).

For a full description, see Deliverable D3C.1 (Rounsevell et al., 2015).

2.2.3. Iberia

The Iberian case study focused on the transboundary river basin of the Tagus River and explored issued of transboundary water usage in a dry area. Land uses along the river basin, such as agriculture, forestry and energy production are vulnerable to land use changes upstream and were also explored in the case study.

Models used:

- Physically-based model: LandClim (agroforestry productivity);
- Physically-based model: SWIM (hydrology, including water transfers).

For a full description, see Deliverable D3C.1 (Rounsevell et al., 2015).

2.2.4. Hungary

The Hungarian case study analysed climate change impacts at the local scale in two Hungarian communities: Szekszárd and Veszprém. Three major topics were explored: urban and agricultural land use, water availability and human health. Impacts of high-end climate change on Hungary are likely to be among the strongest in Europe, and the case study offered the opportunity to help key local stakeholders identify ways of increasing resilience to climate change.

Models used:

- Statistical model: ALLOCATION (population and urban land use);
- Agent-based model: LYR (Lyme disease);
- Physically-based model: SWIM (hydrology);
- Statistical model: HEET (Heat stress mortality);
- Agent-based model: Aporia (agricultural land use).

For a full description, see Deliverable D3C.1 (Rounsevell et al., 2015).

2.2.5. Central Asia (EU external): Implication for the EU of cross-border climate change

This case study based in Central Asia explored high-end scenarios and cross-border impacts. This is an important field to explore as cross-border impact analysis is a relatively immature field of research, and the inclusion of a case study outside the borders of Europe allowed this to be developed. The case study focused on cross-border dynamics of the Central Asian republics of Kazakhstan, Uzbekistan, Turkmenistan, Kyrgyzstan and Tajikistan as well as taking into consideration geo-political dynamics with Russia and China (see Deliverable D3A.2; Benzie et al., 2017). The impacts of activities in Central Asia on the EU are analysed, but also what sort of adaptation strategies might be required to deal with external challenges. A more detailed account of the Central Asia case study is given in Section 5 of this deliverable.

2.3. European sub-regions

Europe was sub-divided into eight sub-regions following Rockel & Worth (2007) for the synthesis and comparison of climate change impacts across scales (Figure 1). The same sub-regions were used for the sensitivity analysis conducted in the project using an impact response surface (IRS) approach (see Annex B of Deliverable D3.1 [Carter et al., 2015]; Fronzek et al., 2018; and Section 4 of this deliverable).

For this deliverable, the sub-regions of particular importance are:

- British Isles, used in some analyses as a proxy for the Scotland case study;
- Iberia, used in some analysis as a proxy for the Iberian case study;
- East Europe, used in some analysis as a proxy for the Hungarian case study.

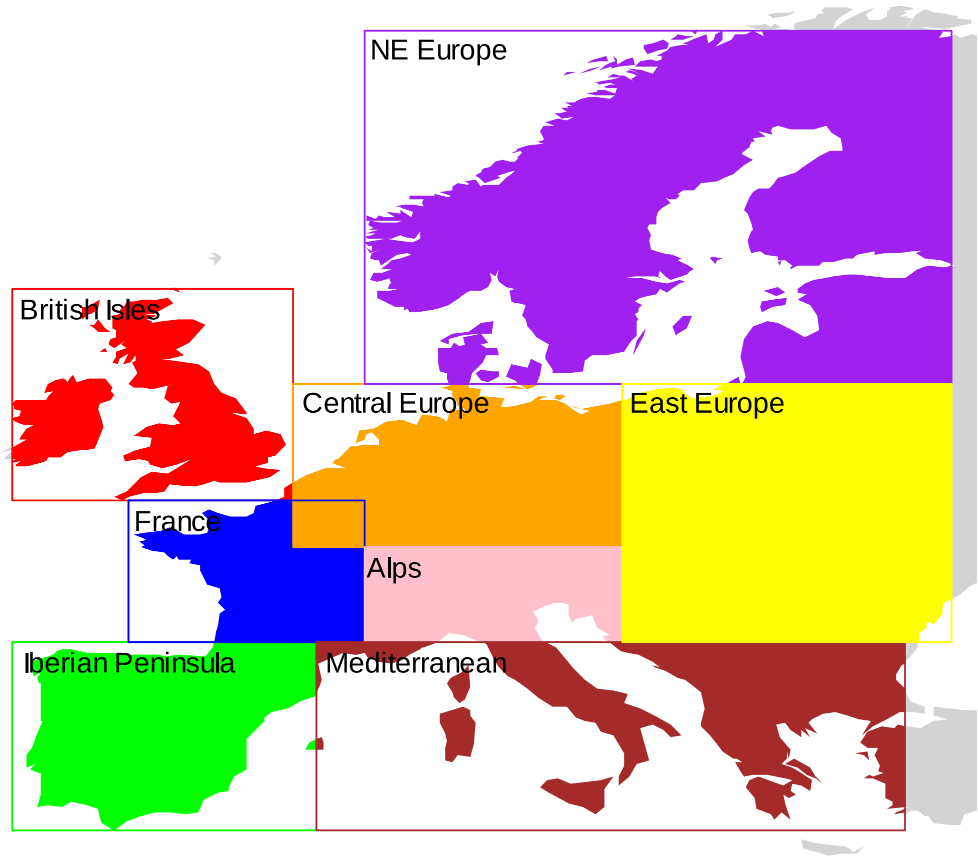


Figure 1: European sub-regions. Source: Fronzek et al. (2018), modified from Rockel and Worth (2007).

3. Quantitative inter-model and cross-scale comparisons

This section describes a set of detailed quantitative inter-model and cross-scale comparisons for the key sectors of: agriculture (crop yields); forestry; water; land use; and urban land use and population growth. Brief model descriptions are provided for each sector-based comparison within the following sub-sections.

3.1. Crop yields

3.1.1. Inter-model comparison

Crop yield data for Europe from the global models within the Inter-Sectoral Impact Model Intercomparison project (ISIMIP) were compared to outputs from the IMPRESSIONS IAP2. ISIMIP yield data for four crops (wheat, maize, soy and rapeseed) from seven crop models (EPIC, GEPIC, IMAGE, LPJ-GUESS, LPJmL, pDSSAT and PEGASUS) were extracted from those 0.5° x 0.5° grid cells within the IMPRESSIONS European domain (number of grid-cells varying between 3646 and 4979 across the different crop models). The IAP2 output has a finer spatial resolution of 10' x 10' (and 23871 grid-cells over Europe). A short introduction to the two model sets and results from the model intercomparison are given below.

<u>3.1.1.1 IMPRESSIONS Integrated Assessment Platform 2 (IAP2)</u>

The IAP2 is an interactive, exploratory, web-based tool for simulating climate change impacts and vulnerabilities on a range of sectors (Harrison et al., 2018). The Platform integrates a suite of models of urban development, water resources, coasts, agriculture and forests, and biodiversity to simulate the spatial effects of different climatic and socio-economic scenarios across Europe. IAP2 builds on IAP1 (Harrison et al., 2015a), developed in the EU CLIMSAVE project, by integrating new climate and socio-economic scenarios and extending model projections to 2100. IAP1 has been applied widely in climate change impact, adaptation and vulnerability assessments, in robust policy analysis and has been tested extensively through model sensitivity and uncertainty analyses (Harrison et al., 2015b; Dunford et al., 2015; Brown et al., 2015; Jäger et al., 2015; Kebede et al., 2015). The Platform operates at a spatial resolution of 10 arcmin x 10 arcmin grid-cells (and 23871 grid-cells over Europe), although multiple soil types are represented in each grid-cell.

<u>3.1.1.2 ISIMIP</u>

A comprehensive review of the ISIMIP crop models, including their input data and key characteristics and differences in their modelling approaches, can be found in Rosenzweig et al. (2014). A brief description of the models along with representative description papers is given here.

Three of the seven models (EPIC, GEPIC and pDSSAT) are site-based crop models, a category of crop models developed for field-scale modelling and representation of dynamic feedbacks between the crops, soil and the atmosphere and the interactions with crop management practices (Rosenzweig et al., 2014). EPIC (Environment Policy Integrated Climate, Izaurralde et al., 2006) is a agro-ecosystem model that simulates crop growth, considering crop rotation and agricultural management options and was originally developed as a tool for the assessment of erosion effects on soil productivity. GEPIC (Geographic Information System (GIS)-based Environmental Policy Integrated Climate Model, Liu et al., 2007) is the GIS-based version of EPIC. EPIC and GEPIC employ the same core model but for the ISIMIP experiment, different soil parameters and management options were used, and these differences cause variations in the final results of the two models. Similar to the philosophy of EPIC and GEPIC, pDSSAT (parallel Decision Support System for Agro-technology Transfer, Elliott et al., 2014; Jones et al., 2003) simulates cropping systems as growth, development and yield of the crops in the system along with the interactions with crop management, soil, water and carbon.

Three other models (LPJ-GUESS, LPJmL and PEGASUS) belong to the family of agro-ecosystem models, which focuses on the simulation of carbon, nitrogen, energy and soil water fluxes (Rosenzweig et al., 2014). Both LPJ-GUESS (Lund-Potsdam-Jena General Ecosystem Simulator with Managed Land, Smith et al., 2001) and LPJmL (Lund-Potsdam-Jena managed Land Dynamic Global Vegetation and Water Balance Model, Fader et al., 2010) are dynamic vegetation models. Representation of crops was included in these models to improve the dynamic water and carbon cycle simulation. PEGASUS (Predicting Ecosystem Goods And Services Using Scenarios model, Deryng et al., 2011) simulates crop carbon dynamics coupled with surface energy and soil water exchange schemes, based on crop management data. Finally, IMAGE (Integrated Model to Assess the Global Environmental Change, Bouwman et al., 2006) is an agro-ecological model initially developed as an Integrated Assessment Model for climate change impacts. In later versions, the agro-ecological zone methodology was incorporated in the model to simulate crop development.

<u>3.1.1.3 Comparison</u>

For comparability, the ISIMIP and IAP2 simulations use climate data from the GFDL-ESM2M global climate model focused on the RCP8.5 emissions scenario, although the GFDL-ESM2M climate data within the IAP2 are downscaled using the RCA4 regional climate model. In order to focus on the response of the crop yield models to climate-only perturbations, the socio-economic inputs were maintained at the baseline values. The comparison was performed across different spatial scales, starting from the European scale and focusing on the regional and national level. Other assumptions were made about sowing and harvesting dates. In the IAP2, sowing and harvest dates were fixed as a characteristic of each crop (Audsley et al. 2015). Within the ISIMIP models, different approaches were taken, with EPIC, LPJ-GUESS, LPJmL and pDSSAT having a fixed planting window and GEPIC, IMAGE and PEGASUS having a dynamic sowing window, which allows adaptation to climate change (Rosenzweig et al. 2014).

A distinctive feature of the IAP2 compared to the ISIMIP models, is that it includes autonomous adaptation to satisfy the supply-demand balance so that it allocates crops to the most profitable and climatically appropriate regions to meet demand, rather than growing them in every grid-cell of the domain (even climatically unsuitable cells), as with the ISIMIP models. To investigate the effect of this feature in the simulations, IAP2 yield outputs were first compared to ISIMIP outputs for the whole ISIMIP domain and secondly to ISIMIP outputs for those grid-cells corresponding to the areas where the IAP2 selects the crop (non-zero crop yield mask).

3.1.2. Results

Projected changes in simulated wheat, soy and rapeseed yield in the 2050s relative to the baseline averaged over sub-regions of Europe are shown in Figure 2. Three key features can be observed in this figure. First, when all the grid cells of the domain are included in the calculations, substantial variations between the ISIMIP models and between ISIMIP models and IAP2 can be observed. However, when the non-zero IAP2 mask is imposed on the ISIMIP domain, removing those parts of Europe which the IAP2 considers to be climatically unsuitable or less profitable (due to lower productivity than competing areas of Europe), the distribution of the ISIMIP models' yields changes, with the median yields moving closer to the IAP2 values and with less zero or very low yields. It is also interesting to note that the distributions of the ISIMIP models more closely resemble each other after the ISIMIP non-zero mask is applied. These results suggest that the IAP2's selection of the most climatically appropriate grid cells for growing a given crop improves model performance compared to the spatially uniform (and agronomically unrealistic) approach adopted by the global ISIMIP models. Lacking this selective feature, ISIMIP models are forced to simulate crops in all the grid-boxes of their domain, resulting in misleading very low yields in the areas that are not suitable for a particular crop.

Second, these effects are more pronounced for crops that are grown less across Europe (grain maize and soy), which have more constrained climatically-suitable conditions compared with more ubiquitous crops such as wheat. Finally, there appears to be a systematic difference between IAP2 and the more limited set of ISIMIP models for the simulated yields for oilseed rape, with the maximum yield within the ISIMIP domain being around 5 t/ha. Whilst the Eurostat databases do not contain any yield information for oilseed rape, the average reported yield across 17 UK sites from 2014 to 2017 is 5.48 t/ha, which is included in the IAP2's distribution, but cannot be captured by either of the two ISIMIP models for which rapeseed yield simulations are available.

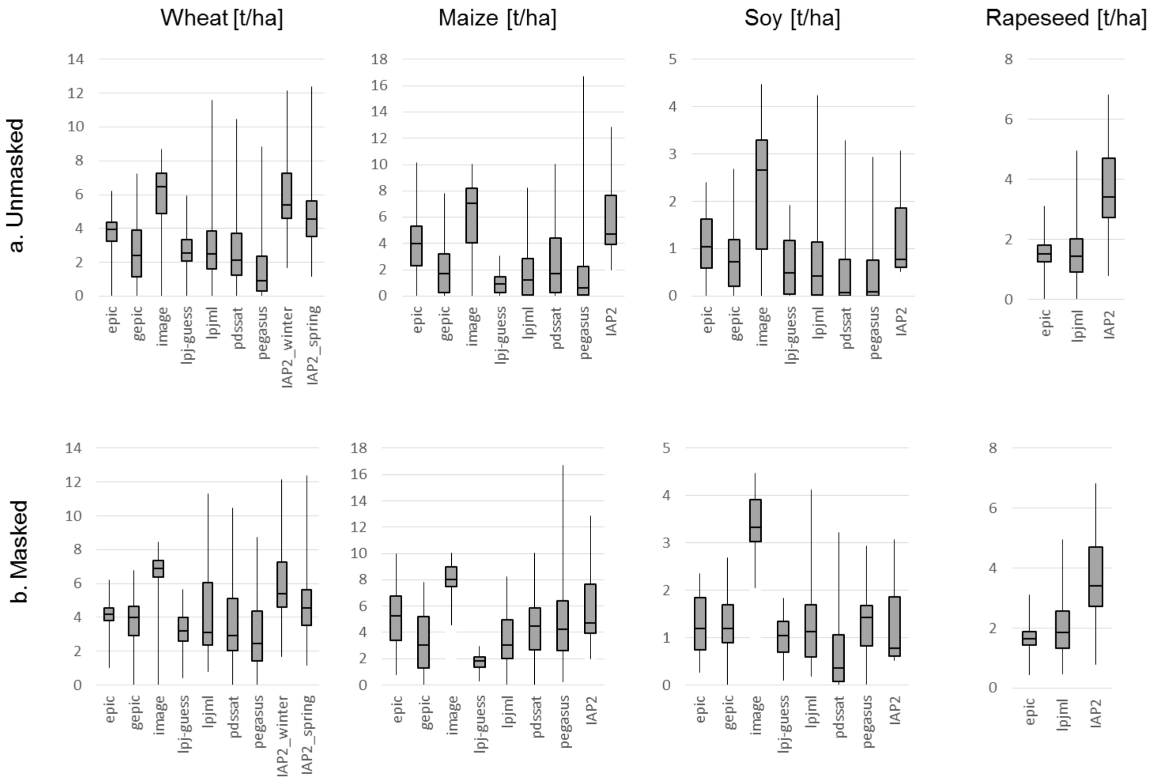


Figure 2: Box and whisker plots for crop yield values across Europe, for the ISIMIP models and IAP2. (a) Unmasked: all the grid cells of the ISIMIP models' domain are included, (b) Masked: only the grid-boxes where IAP2 has non-zero values are selected from the ISIMIP models' domain. Results are shown for four crops: wheat, maize, soy and rapeseed. Boxes represent the inter-quartile range and the median and whiskers the minimum and maximum crop yield values.

A comparison between ISIMIP and IAP2 modelled yields with Eurostat wheat and soy yield data at the country level (Figure 3) provides further insights into benchmarking of model performance. For most countries, the national-average Eurostat wheat and soy yields are captured by the minimum to maximum range of national-average yields of the ISIMIP models, which is, however, quite broad. The IAP2 shows a good performance in simulating wheat yields for most countries, yet consistently underestimates the national-average soy yield. As IAP2 has been calibrated against observed crop yields in Europe, its results are better for wheat - a crop that is widespread in Europe. In contrast, the IAP2's performance for soy is likely to be constrained because of its limited production area in Europe meaning that a proper calibration of the model was more difficult to achieve. Thus, in the case of specialist crops that are rarely grown in Europe, the globally calibrated ISIMIP models appear to give a better representation of the yield.

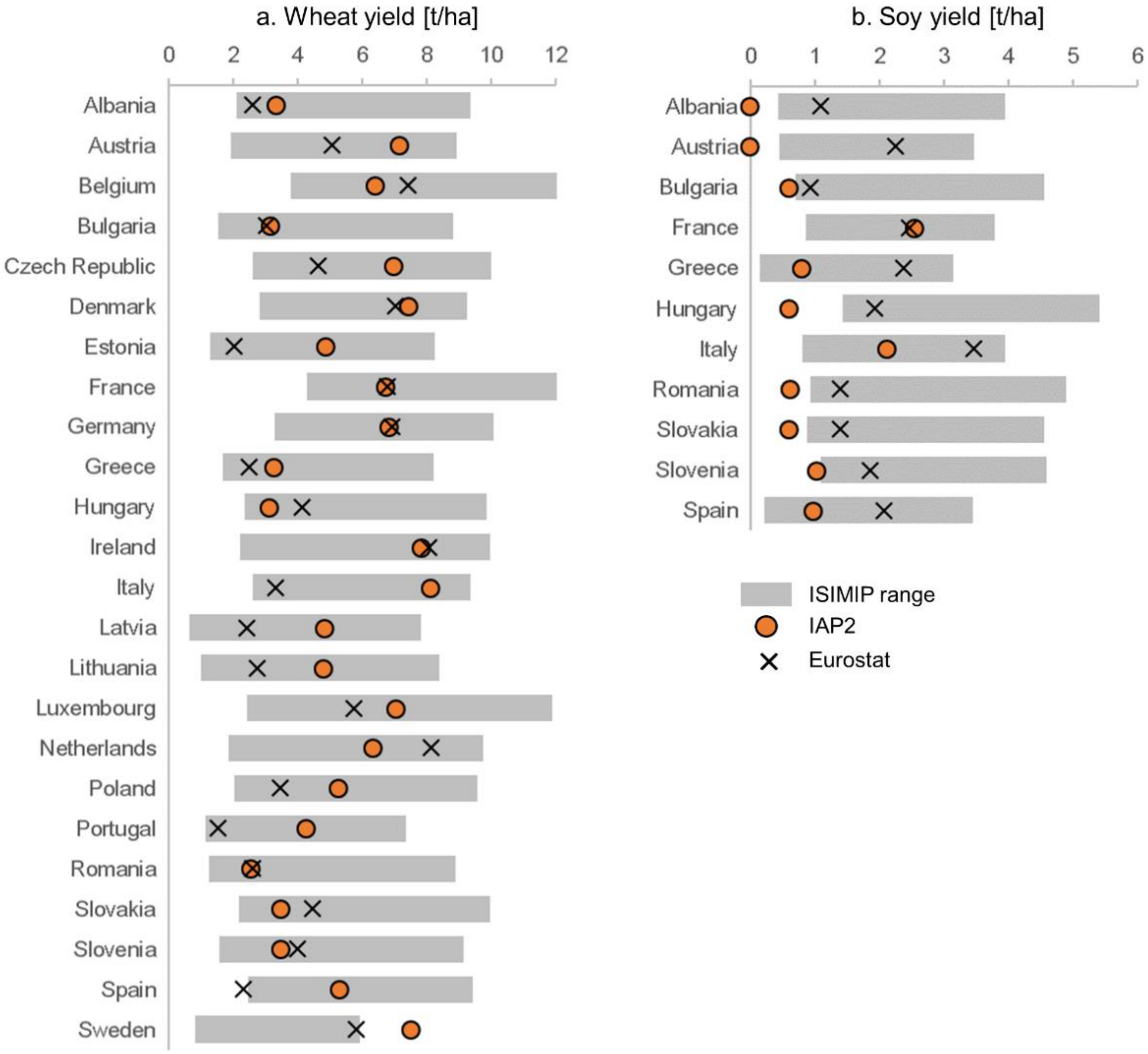


Figure 3: Country-level average annual yields of (a) wheat [t/ha] and (b) soy [t/ha] for the baseline period, for the range of the seven ISIMIP models, IAP2 and crop yield data from Eurostat. Results are shown only for the countries for which Eurostat data were available (i.e. not including the UK).

Projected changes in simulated wheat, soy and rapeseed yield in the 2050s compared to baseline, averaged over sub-regions of Europe are shown in Figure 4. The ISIMIP data shown have been masked based on the non-zero IAP2 domain. For all the crops, there is a spatial variability in the magnitude and direction of the projected changes between models, which is not always reflected in the change calculated at the pan-European scale. While there is not always an agreement on the sign of the projected yield change between the ISIMIP models, the IAP2 generally projects the same direction of change as the majority of ISIMIP models.

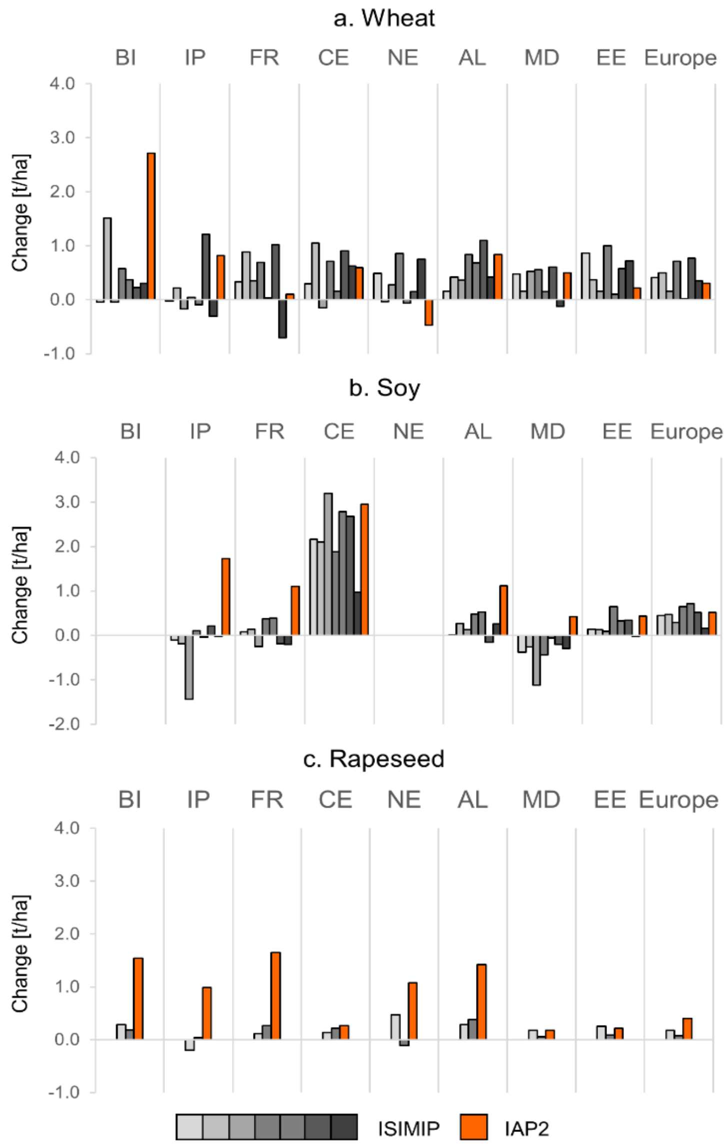


Figure 4: Regionally averaged absolute changes in (a) wheat, (b) soy and (c) rapeseed yield in the 2050s under RCP8.5 compared to baseline, for the ISIMIP models and IAP2 for the eight European sub-regions defined in Figure 1.

3.2. Forest productivity

For the forestry sector, simulation studies were conducted independently for the different case studies and scales. These analyses of the impact of climate change highlighted that both the continental-scale patterns and local specificities were complementary and highly useful to assess future forest management and adaptation strategies.

3.2.1. Inter-model comparison

Forest productivity was modelled using two related models: ForClim and LandClim. ForClim (Bugmann and Solomon, 2000; Shao et al., 2001) was used to simulate forest development and productivity, on a 5km grid covering Scotland, for different management (i.e. different tree species) and climate change scenarios. ForClim is a cohort-based, stand scale, dynamic vegetation model that was developed to analyse successional pathways of various forest types (Bugmann and Solomon, 2000; Shao et al., 2001). Based on the theory of patch dynamics, tree development (growth), establishment and mortality are simulated with an annual time step for small areas ("patches"), while the influence of climate and ecological processes is taken into consideration using a minimum of ecological assumptions. No interaction is assumed between trees of adjacent patches, i.e. the successional pattern at larger scales (forest stand to landscape) is obtained by averaging the simulation results from many patches (Bugmann, 2001). ForClim is composed of four independent sub-models for weather (computes relevant bioclimatic variables), water (computes an annual site-specific drought index), plant (calculates establishment, growth and mortality of trees on the forest patch) and management by simulating several cutting/harvesting and thinning techniques defined by the type (e.g. clear cutting, 'plentering'), and the frequency and intensity of management operations.

The spatially-explicit landscape forest model LandClim (v1.6) (Schumacher et al., 2004) was used in the Iberian case study at the scale of the entire Tagus river basin to simulate the response of tree-based, land uses (Montado, pine and olive plantations, and natural forests) under various climate change scenarios, fire regimes, and management strategies. LandClim is a stochastic forest landscape model designed to simulate long-term forest dynamics and the impact of climate, disturbances (i.e. fire, wind, bark beetles) and management on a wide range of ecosystem services. The model is spatially-explicit and represents the landscape on a 25 m x 25 m grid. Within each grid cell, vegetation dynamics are represented using a simplified forest gap model where different cohorts represent trees of the same species and age (Schumacher et al., 2004). Processes such as establishment, growth, mortality and competition for light and water are modelled explicitly as being driven by temperature, precipitation, soil properties and topography. Establishment and mortality are stochastic processes, thus the environment influences the probability of an event, but the event itself is determined by a uniform random number generator. Spatially-explicit processes such as seed dispersal, disturbances and management connect individual grid cells. By using different time steps for different processes, LandClim can efficiently simulate large landscapes while maintaining a relatively high degree of detail at the local scale. The model has been used to simulate a variety of forest types and forest processes in Central Europe (e.g. Schumacher et al., 2006; Temperli et al., 2012; Elkin et al., 2013) and the Mediterranean (Henne et al., 2013; Henne et al., 2015), producing results that were consistent with empirical data.

Cross-scale simulation results between ForClim and LandClim were not directly comparable because the simulations were based on distinctly different assumptions, including species choice, forest management regime, and the output variables that were considered (as described above). Yet, the simulations across different scales provide complementary information and, together, a rich picture of the future of European forests arises.

3.2.2. Results

At the continental scale, climate change is projected to have positive impacts on forest productivity in cold-limited and water-unlimited areas, and rather negative impacts in areas that are or will be water-limited. Productivity maps for Scots pine (*Pinus sylvestris*) serve to illustrate this pattern at the European scale (Figure 5), with enhanced productivity projected under all climate change scenarios in Northern Europe and in the mountain areas of Central Europe, while productivity decreases in Southern and Eastern Europe, although the severity and extent of the negative impacts depends strongly on the severity of climate change.

These projections are consistent with those made in the regional case studies, although the set of species is different. In Scotland, the regional model application simulates an increase in timber production in the Scottish Highlands (Figure 6), but this is limited to the highest elevations for Scots pine, whereas it is also projected to occur at lower elevations for Sitka spruce (*Picea sitchensis*) and Douglas-fir (*Pseudotsuga menziesii*) (results not shown). The two latter (exotic) species may thus be considered as good candidate species for future afforestation in Scotland.

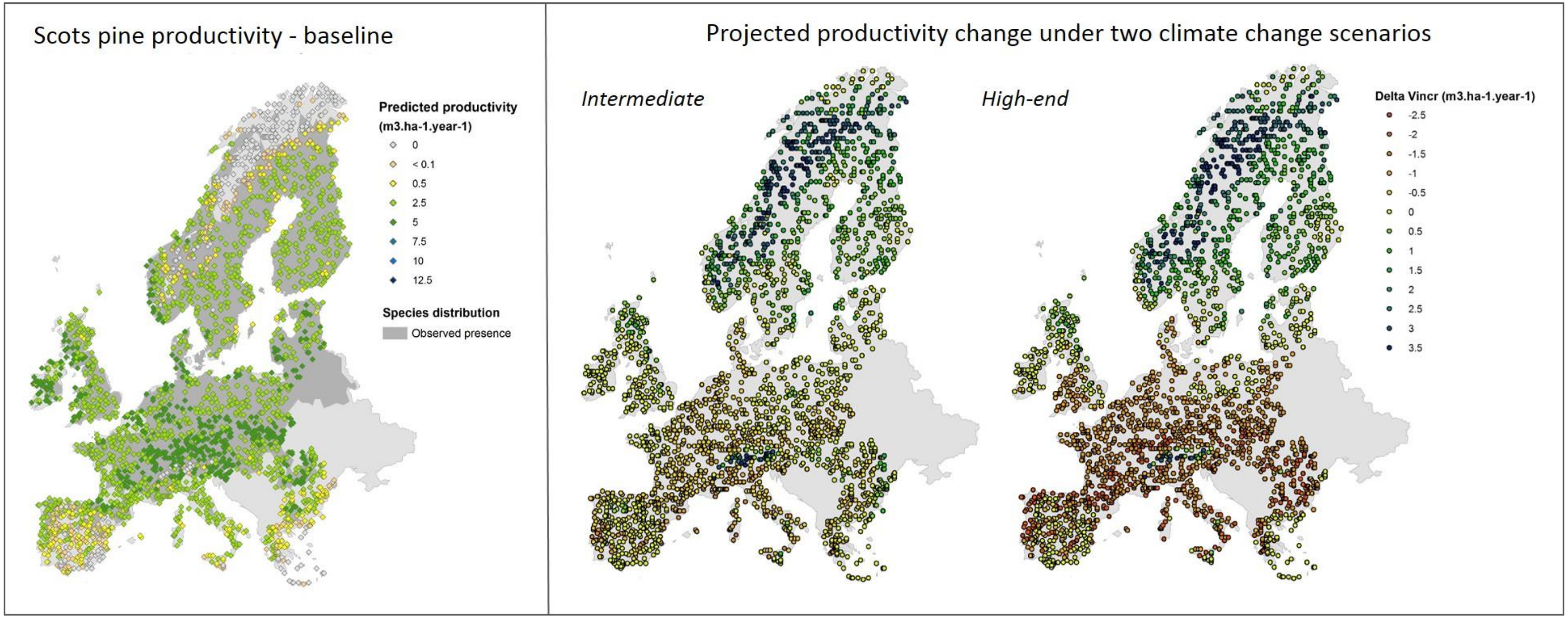


Figure 5: Potential productivity of Scots pine under current climate conditions (left) and projected change by 2100 under two climate scenarios (right). The intermediate climate change scenario (middle) refers to the HadGEM2-ES-RCA4 climate model for RCP4.5 and the high-end scenario to HadGEM2-ES-RCA4 for RCP8.5. Negative values indicate a loss compared to current climate, and positive values show an increase compared to current climate.

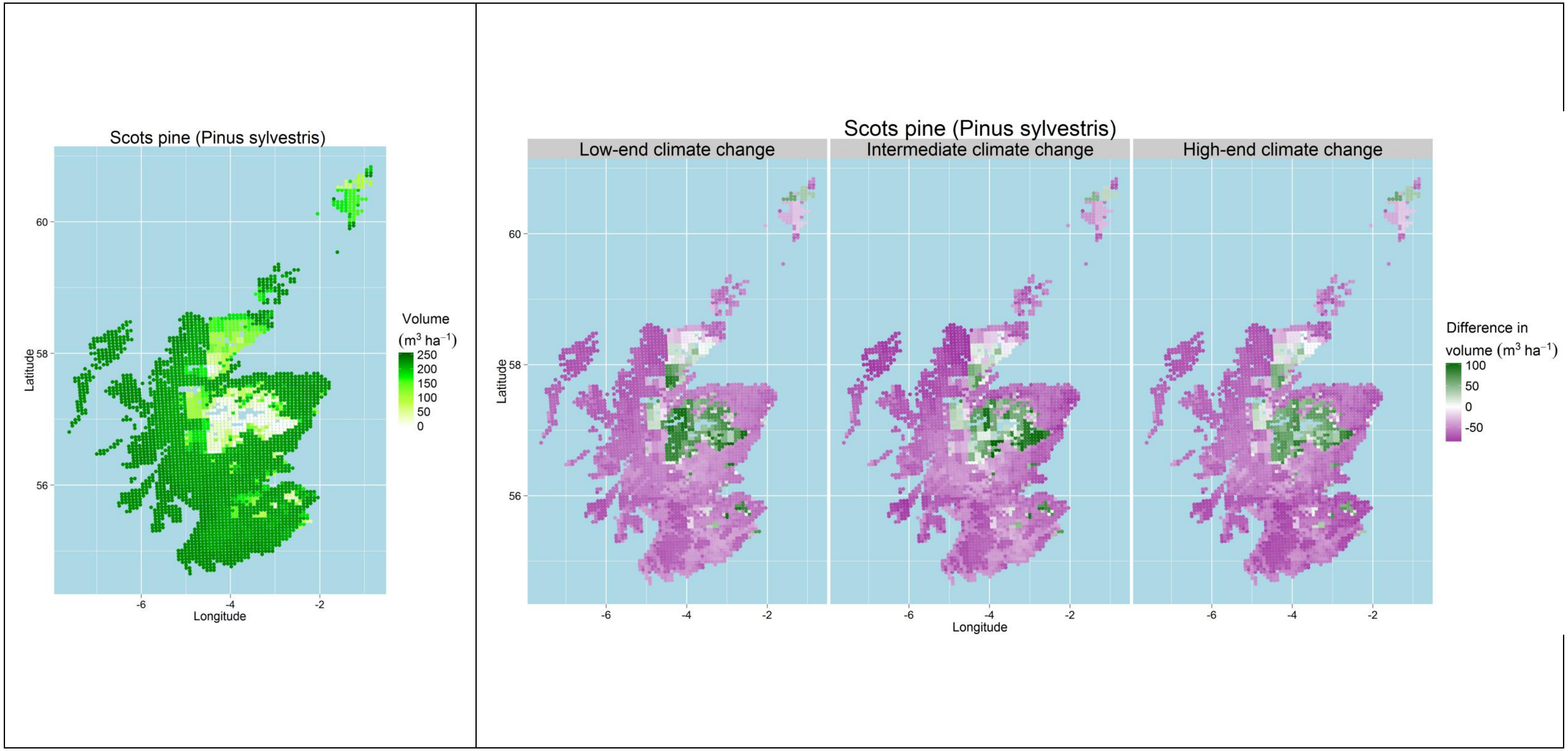


Figure 6: Harvested volume of Scots pine grown under current climate conditions (left) and under three climate scenarios (right). The total harvested volume is shown for current climate, and the absolute change in volume is shown under future climate change. Negative values (purple) indicate a decrease in volume and positive values (green) indicate increases in volume in the future. The low-end climate change scenario refers to the GFDL-ESM2M/RCA4 climate model for RCP4.5. The intermediate climate change scenario (middle) refers to HadGEM2-ES-RCA4 for RCP4.5 and the high-end scenario to HadGEM2-ES-RCA4 for RCP8.5.

In the Iberian case study, the model projects mostly negative effects that, combined with high grazing pressure (i.e. cattle in the Montado agro-forest system), leads to significant losses in cork production, especially under high-end climate change (Figure 7). These results (cork production) cannot be compared directly to the general forest productivity results from the continental-scale analysis, but they at least agree in their direction of change. In this case, maintaining ecosystem service provisioning at current levels would only be possible under low or intermediate climate change, with a reduction in grazing pressure to historic levels.

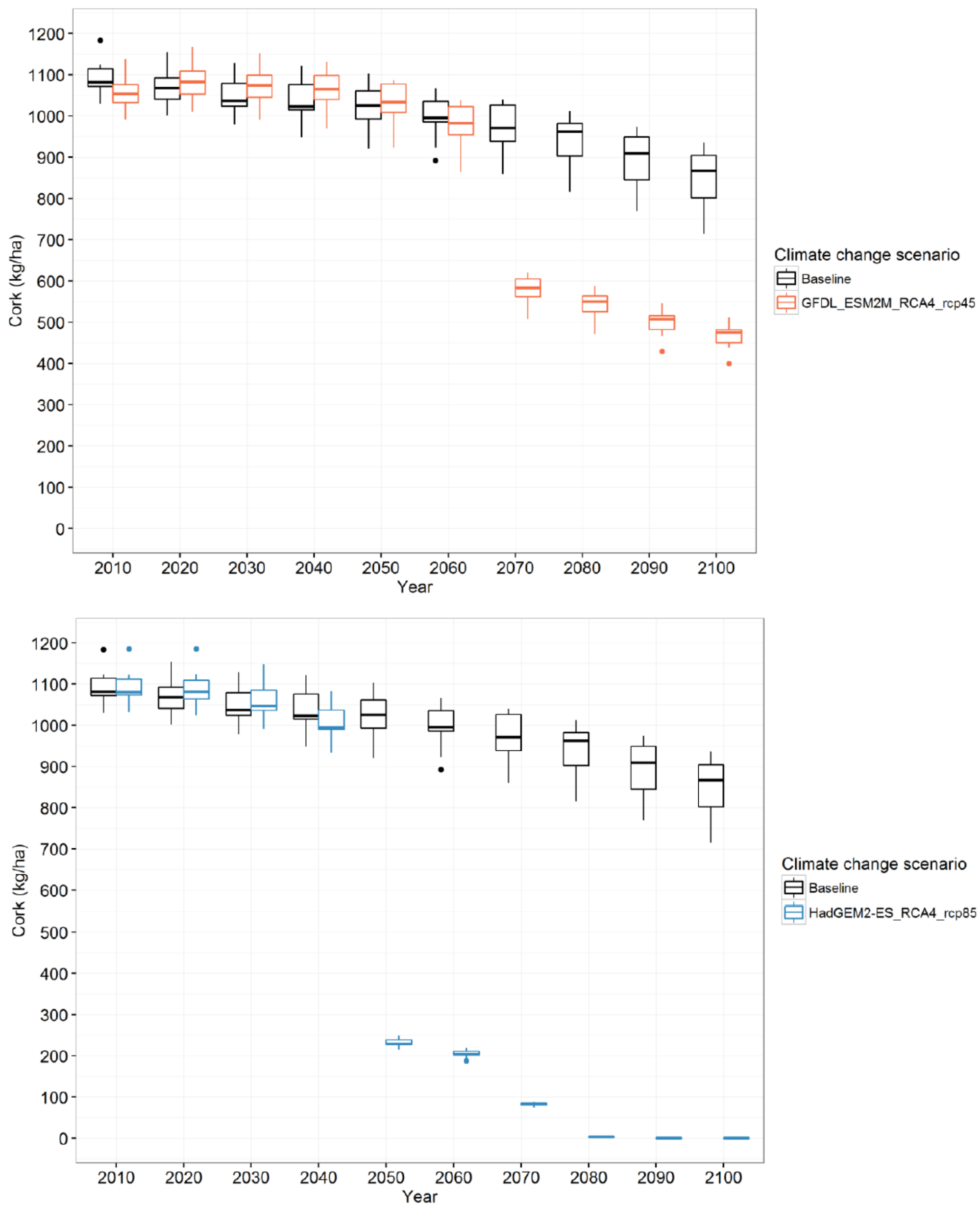


Figure 7: Projections of future decadal cork production (from Cork oak, Quercus suber) under three climate change scenarios. The first scenario assumes constant climatic conditions similar to baseline (black), the second (orange, top) represents an intermediate climate change scenario (GFDL-ESM2M-RCA4 for RCP4.5) and the third (blue, below) represents a high-end climate change scenario (HadGEM2-ES-RCA4 for RCP8.5).

3.3. Water

3.3.1. Inter-model comparison

Several hydrological and water resource models were applied in IMPRESSIONS, in particular:

- CFFlood, simulating coastal and fluvial flooding;
- WaterGAP meta model (WGMM), simulating changes in water resources and water use, and consequential water stress levels;
- SWIM model, a process-based catchment scale model used for the simulation of daily river discharge rates.

The results of the SWIM model can, in principle, be compared with both CFFlood and the WaterGAP meta model. However, because the SWIM model was not used for flood simulations in IMPRESSIONS, the model intercomparison was only possible between SWIM and WGMM. Furthermore, because of the spatial resolution of WGMM, the model intercomparison was only possible for three out of seven river basins, simulated with the SWIM Model.

A short introduction to the two models and results from the model intercomparison are given below.

3.3.1.1 WaterGAP meta model

The WaterGAP Meta Model (WGMM) was used in the IAP2 and rIAM to assess both the impact of climate change on water resources and the change in water demand for human use due to socio-economic development. WGMM is designed to be an emulator for the global hydrological model WaterGAP3 (Water – Global Assessment and Prognosis) (Verzano, 2009). Originally, WaterGAP3 operates on a five arc minute grid with daily internal time steps. In order to reduce runtime considerably, the spatial detail of WGMM was reduced from more than 180,000 grid cells for Europe in WaterGAP3 to spatial units with an area larger than 10,000 km². These spatial units, hereafter referred to as river basins, are made up either by single large river basins (split into three sub-basins for the Danube) or clusters of smaller, neighbouring river basins with similar hydro-geographic properties. Moreover, the input data requirements are largely reduced as long-term statistics over a 30-year period are computed instead of daily or monthly time series.

For each river basin, the meta-model computes the change in long-term (30 years) average water availability (WA), resulting from changes in mean annual precipitation and air temperature compared to a baseline value. The meta-model relies on look-up tables populated with simulated WA of pre-run WaterGAP3 simulations for the baseline period (IAP2: CRU data set 1971-2000 [Mitchell & Jones, 2005]; rIAM: WATCH WFDEI 1981-2010 [Weedon et al., 2014]) with simultaneously modified mean temperature and precipitation.

3.3.1.2 Soil and Water Integrated Model

The process-based hydrological model Soil and Water Integrated Model (SWIM) was applied to seven representative river basins in Europe: the Lule, Northern Dvina, Tay, Emån, Rhine, Danube and Tagus, as presented in Figure 8. The basins were selected in order to cover geographic and climatic heterogeneity of the European regions. The selected basins vary significantly in catchment area, climate conditions, as well as the main anthropogenic influences and associated alteration of river flow. 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 in the historical period. The river discharge in the reference and 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. A fuller description of SWIM model is provided in Deliverable D3B.1 (Holman et al., 2015) for the European Case study, as well as in Deliverable D3C.1 (Rounsevell et al., 2015). The Tay, Tagus and Danube river basins (Lobanova et al., 2016, 2017) provide a link to the IMPRESSIONS regional case studies (Scottish, Iberian and Hungarian, respectively).

The SWIM model was able to adequately represent the hydrology of the river catchments to which it was applied. To judge model performance, commonly used criteria were applied – the Nash-Sutcliffe efficiency (NSE; Nash & Sutcliffe, 1970) and the Relative Volume Error (RVE). The values of RVE and NSE obtained in the calibration and validation periods for each of the basins are presented in Deliverable D3B.2 (Holman et al., 2017).

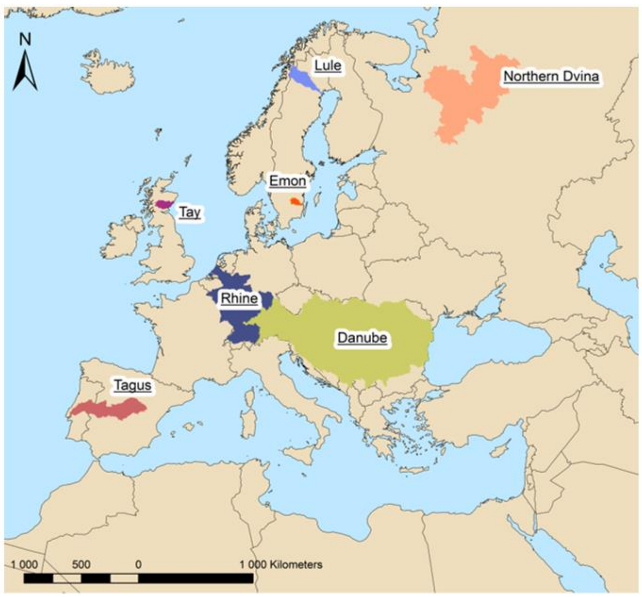


Figure 8*:* The seven river basins modelled using SWIM.

3.3.2. Results

3.3.2.1 Average discharge conditions

In order to test the simplified approach, implemented in WGMM, the results of the changes in water availability, simulated by WGMM, were compared to the results of the SWIM model for the basins of the Danube, the Rhine and the Tagus rivers. Figure 9 presents scatter plots for the three basins showing that the changes in the long-term average river discharge in future periods compared to the reference period from both models are in good agreement (Tagus: R^2=0.66, Rhine: R^2=0.76, Danube: R^2= 0.77). The data in the plot covers all available climate projections (GCM-RCM identified by symbol) based on RCP4.5 (identified by blue colour) and RCP8.5 (red colour) for the periods 2011-2040 (2020s), 2041-2070 (2050s) and 2071-2100 (2080s), where the time slice is identified by symbol size. The largest uncertainty due to climate modelling was observed for the Tagus under RCP8.5, and the largest deviations of WGMM compared to SWIM results were also found for the Tagus River, but under RCP4.5 (see Deliverable D3B.2 [Holman et al., 2017] for quantitative assessment).

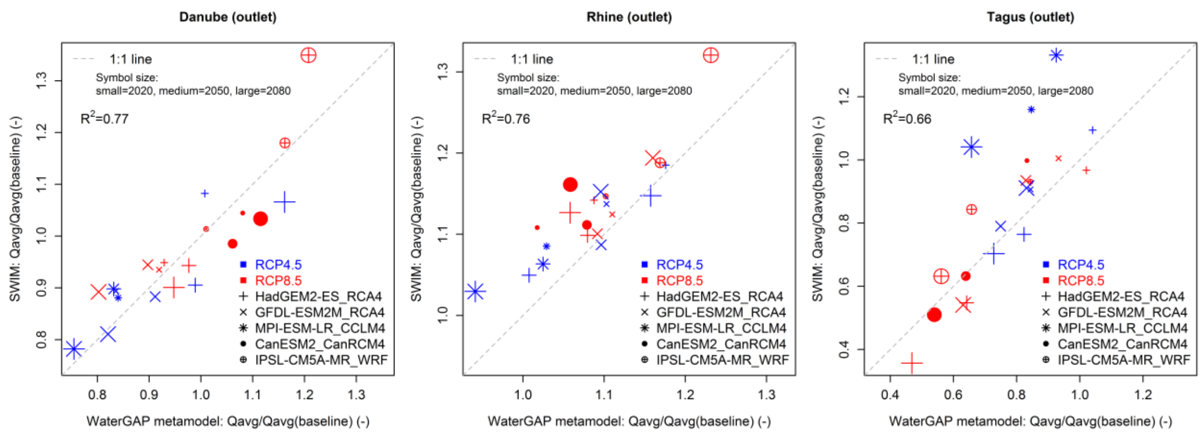


Figure 9: Scatter plot of relationships between changes in the average river discharge in the future periods compared to the reference period modelled by SWIM vs WGMM for the Danube, Rhine and Tagus rivers.

<u>3.3.2.2 Median annual flood discharge</u>

A lower degree of agreement between the WGMM and SWIM was found when looking at the median annual flood discharge (QMED) (Figure 10). The correlation coefficients in the cases of the Rhine (R^2=0.29) and the Tagus (R^2=0.24) are low. The estimated changes of QMED from WGMM are systematically lower compared to those of SWIM for the Rhine. For the Tagus, WGMM mainly projects a decrease in QMED while SWIM also shows strong increases.

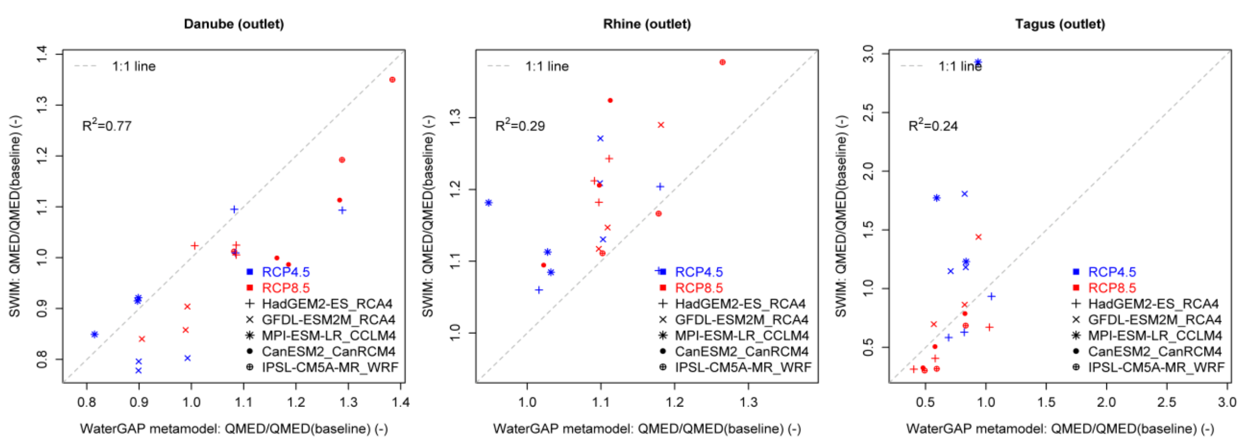


Figure 10: Scatter plot of change in median annual flood discharge (QMED) modelled by SWIM vs WGMM for the Danube, Rhine and Tagus rivers.

3.3.3. Conclusions

Good agreement between the WGMM and SWIM Models indicates that the river basin specific 2D response surfaces within WGMM provide a suitable approach when looking at the average hydrological conditions in the river basins. The poor agreement found for the median annual flood discharge, QMED, may be explained by the fact that WGMM does not employ real climate data time series, but is based on the simple assumption that precipitation changes by a constant factor in each precipitation event. This constant factor is derived as the ratio of long-term mean annual precipitation in the scenario and the baseline period. For example, in the Tagus river basin, a decline in mean annual precipitation is assumed in WGMM, which also leads to decreasing QMED. By contrast, SWIM projects an increase in the QMED under the RCP4.5 scenario. The SWIM model takes into account the simulated precipitation pattern and dynamics, which may also bias the simulation results, especially when looking at the multi-model means. This is apparent for the RCP4.5 scenario where the multi-model spread for the first and second future time slices for the Tagus river basin is relatively large, as one model projects strong increases in the discharge and two predict strong decreases. This affects the multi-model mean and can explain the projected increase in the QMED (for mean annual monthly discharge projections of the Tagus river, see D3B.2 [Holman et al., 2017]). On the other hand, when conducting the model intercomparison of climate change impact assessment results, it is worth assessing the performance of both models on the observed dynamics of the river basins under consideration. A comparison of the WGMM and SWIM models for the historical period representation was not conducted in the IMPRESSIONS project.

Previously, the performance in the calibration and validation period for several river basins of the SWIM model and the "parent" model of the WGMM (i.e. WaterGAP3 model) were compared within the framework of the ISIMIP Inter-sectoral Model Intercomparison Project. Huang et al. (2016) conducted a comparison of the performance of regional hydrological models for 12 river basins worldwide. The intercomparison exercise also included the WaterGAP3 regionalised version of the model. In general, the WaterGAP3 model was less accurate in reproducing the average discharge conditions in the basins than the regional models. On the other hand, the reproduction of the low and high flow conditions was difficult for all models applied to the river basins, and to properly assess these, each model has to be calibrated for extreme conditions.

In general, the simulations of climate change impacts from the SWIM model might be more credible than those of WGMM, as the SWIM model is calibrated and validated for each river basin and employs real climate variables data series; on the one hand, this helps to preserve the physicality of the simulation even if it can, on the other hand, generate additional uncertainties (e.g. due to model parametrization and equifinality effects). However, when aiming at the average flow conditions, WGMM can be helpful, as it requires vastly less computational time and lower effort for set up and calibration of the model than a model of the process-based type, such as SWIM.

3.4. Land use

3.4.1. Inter-model comparison

Two distinct approaches to modelling land use change were undertaken in the IMPRESSIONS project. One relies on an established economic-based model that allocates land uses on the basis of their relative profitability, given the levels of demand for the goods they produce (the SFARMOD model, integrated in the IAP2) (Harrison et al., 2015; 2016). The other uses a newly developed agent-based model of land manager decision-making, developed from the CRAFTY modelling framework (Murray-

Rust et al., 2014; Brown et al., 2016a; Blanco et al., 2017). The former approach constrains production levels to meet demand levels using a pseudo-optimal land use configuration, while the latter allows the land use configuration to emerge from individual-level decision-making without necessarily meeting demand levels. As such, these models represent distinct paradigms for modelling land system dynamics, built on 'top-down' and 'bottom-up' conceptualisation of the system respectively (Brown et al., 2016b).

This fundamental difference in modelling approach makes a comparison of model outputs particularly valuable. To facilitate this and to ensure that a fair comparison is possible, the application of CRAFTY within IMPRESSIONS (CRAFTY-EU) used IAP2 outputs for input variables wherever possible, and therefore effectively provides an alternative land use model within the same climatic, socio-economic and cross-sectoral context. IAP2 is described in section 3.1.1.1 and CRAFTY is described below, before the comparison procedure and results are presented.

3.4.1.2 CRAFTY-EU

CRAFTY-EU is an application of the CRAFTY framework for agent-based modelling of land use change (Murray-Rust et al., 2014; Brown et al., 2016a; Blanco et al., 2017). The CRAFTY framework allows land use outcomes to be modelled as the result of decision-making by agents, each of which can represent an individual or multiple land managers, and which produce a range of ecosystem services. Production levels are determined by the natural productivity of the land (defined through a range of 'capitals', as described below), the intensity of land management, and agents' prioritisation of certain ecosystem services. Agents are grouped into Agent Functional Types (AFTs) (Arneth et al., 2014) on the basis of their management intensity and decision-making characteristics, such as degree of focus on profit-generation. Variation within AFTs allows for individual differences in production levels and land management decisions. Social-networks within and between AFTs allow for the diffusion of knowledge and practices that increase production levels. Finally, a population of institutional agents can be defined to represent formal (e.g. governmental) and informal (e.g. social) interests in the land system, which can make defined interventions to try to achieve defined outcomes. CRAFTY-EU is calibrated using crop yields from the IMPRESSIONS IAP2. All necessary input data are derived from this source, ensuring the transparency and internal consistency of the implementation. This model pairing also allows socio-economic and climatic scenarios to be defined on the basis of comprehensive, cross-sectoral simulations of the European land system by IAP2 that have been extensively evaluated, validated and utilised.

3.4.2. Results

Both the IAP2 and CRAFTY-EU were run for the period 2010-2100 under the core IMPRESSIONS RCP x SSP scenario combinations. Following this, results for the 2080s time slice (2071-2100) were extracted and compared on the basis of full spatial maps, aggregate land use proportions (NUTS2 level) and total land use proportions (European level).

Figure 11 shows the results of an experiment in which divergent results from CRAFTY-EU and the IAP2 for the 2080s under the RCP2.6 x SSP1 integrated scenario were tested for robustness to changing food prices in CRAFTY-EU. In the experiment, CRAFTY-EU food prices were steadily increased, eventually reaching a point at which the same level of food production occurred as in the IAP2. At this point the results of the two models were more similar, but still quite distinct in the degree of heterogeneity in land use patterns, with CRAFTY-EU producing relatively heterogeneous patterns compared to the IAP2. Aside from this, the general longitudinal and latitudinal gradients of land use were similar suggesting that, despite the differences in basic assumptions about land use decision-making, the models converge to some extent under similar economic conditions; the models converge more the higher food prices are allowed to rise in CRAFTY-EU.

Figure 12 shows results aggregated across land use classes and spatial areas (to show agricultural intensity and forestry land use within NUTS2 regions). These plots reveal systematic spatial and scenario-dependent variations in the differences between the two models' results, but also some general differences that are highlighted further in Figure 13. Of the spatial differences, the clearest are in northern and southern Europe. In both regions (but especially the north), CRAFTY-EU has considerably more forestry and extensive/marginal land uses than the IAP2, while the IAP2 has considerably more intensive agriculture. In mid-latitudes, CRAFTY-EU tends to have more intensive arable agriculture and forestry, while the IAP2 has more pastoral and extensive agriculture (although this pattern is partially reversed in eastern Europe).

Within the scenarios, there is some tendency for CRAFTY to produce more forestry in low-end climate scenarios and for the IAP2 to produce more extensive agriculture in high-end climate scenarios. The effects of socio-economic scenarios are clearer, with CRAFTY tending to produce more intensive arable agriculture than the IAP2 in SSPs 4 and 5, but the IAP2 producing far more in SSP3. The IAP2 also clearly produces more pastoral agriculture in SSP1.

These differences remain strong, and informative, at the European level where a main conclusion from the model comparison is that CRAFTY-EU tends to produce more forest, while the IAP2 tends to produce more intensive agriculture (as above, in more areas). This general difference is attributable to the IAP2's assumption that food prices will rise, within limits, so that agriculture can expand to profitably meet food demand (allowing for imports), and CRAFTY-EU's contrasting assumption that prices are constrained and more balanced across goods and services (e.g. timber), thereby allowing larger shortfalls in agricultural food production. Another clear difference is in the heterogeneity of land uses, especially under extreme scenarios; the IAP2 produces less spatial diversity due to the underlying soil-climate clusters that were used to facilitate model runtimes, while CRAFTY produces more mixed patterns, reflecting underlying heterogeneity (and freedom) in agent decision-making.

These differences have substantial implications for the provision of ecosystem services, including food, under future global change. As such, the modelling assumptions that generate these differences require considerable scrutiny, particularly in terms of (i) the representativeness of the assumptions of economic rationality in land use decision-making and the extent to which economic priority would and could be given to meeting net food demands in the European agricultural industry, and (ii) the representativeness of an assumption of actor heterogeneity, and about the strength of that heterogeneity. This particular model comparison provides a strong basis for further investigation of these issues.

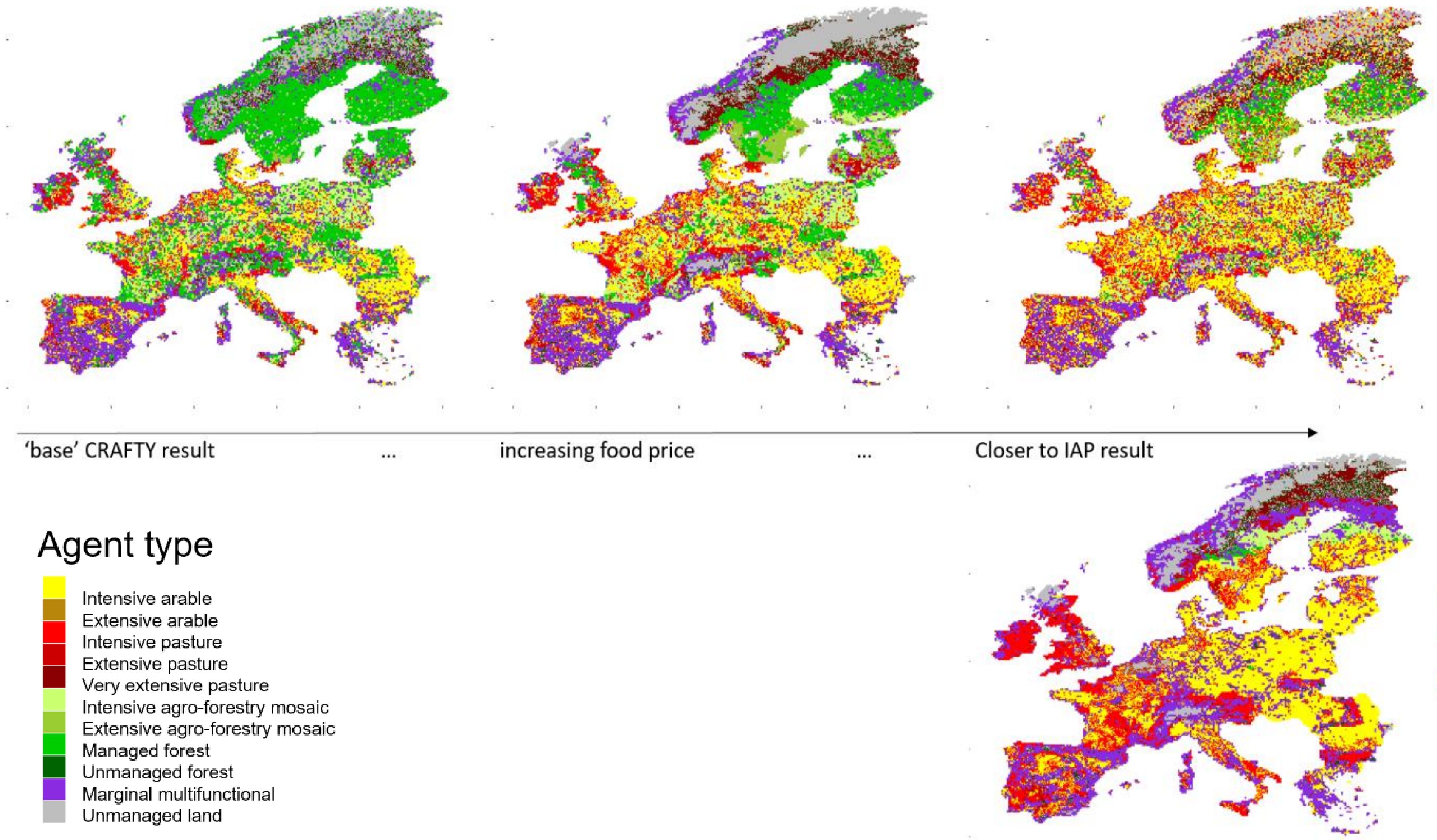
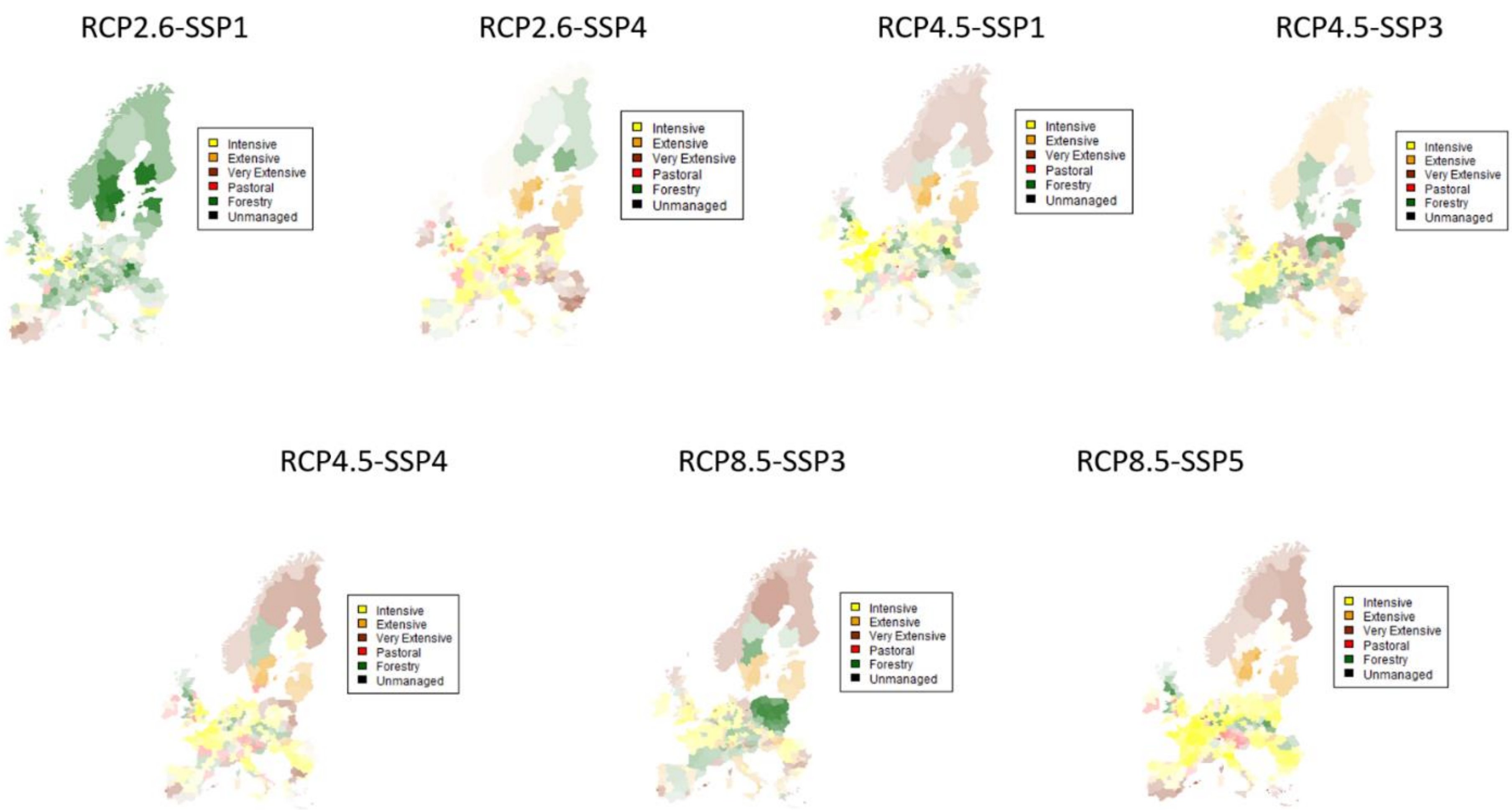


Figure 11: Comparison of CRAFTY-EU (top, different settings) and IAP2 (bottom) for the RCP2.6 x SSP1 scenario.

a) CRAFTY-EU minus IAP2



b) IAP2 minus CRAFTY-EU

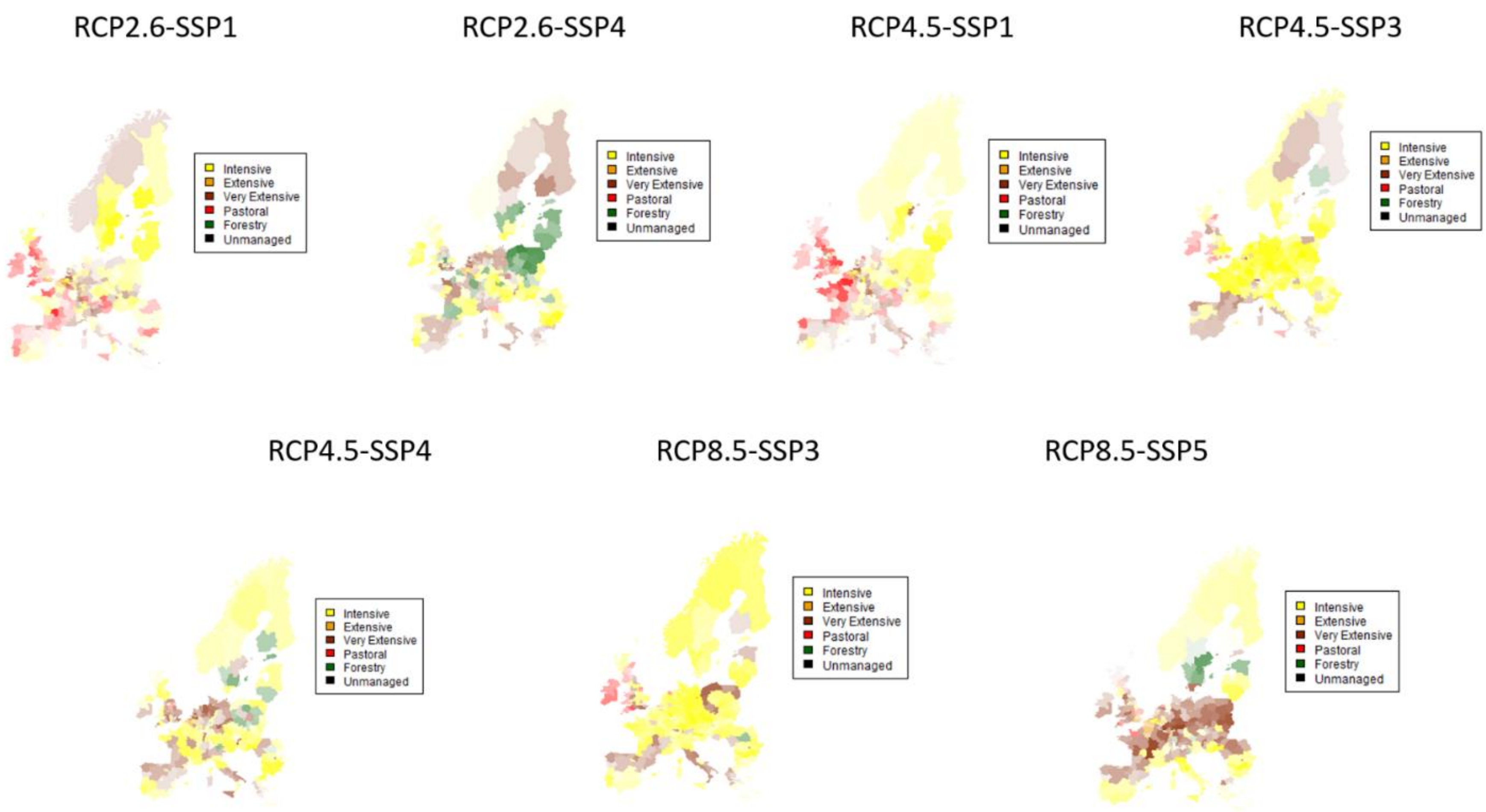


Figure 12: The most substantially over-represented land use type in each European NUTS2 region: (a) for CRAFTY-EU (compared to the IAP2); and (b) for the IAP2 (compared to CRAFTY-EU). Opacity is higher when the difference between the models is greater.

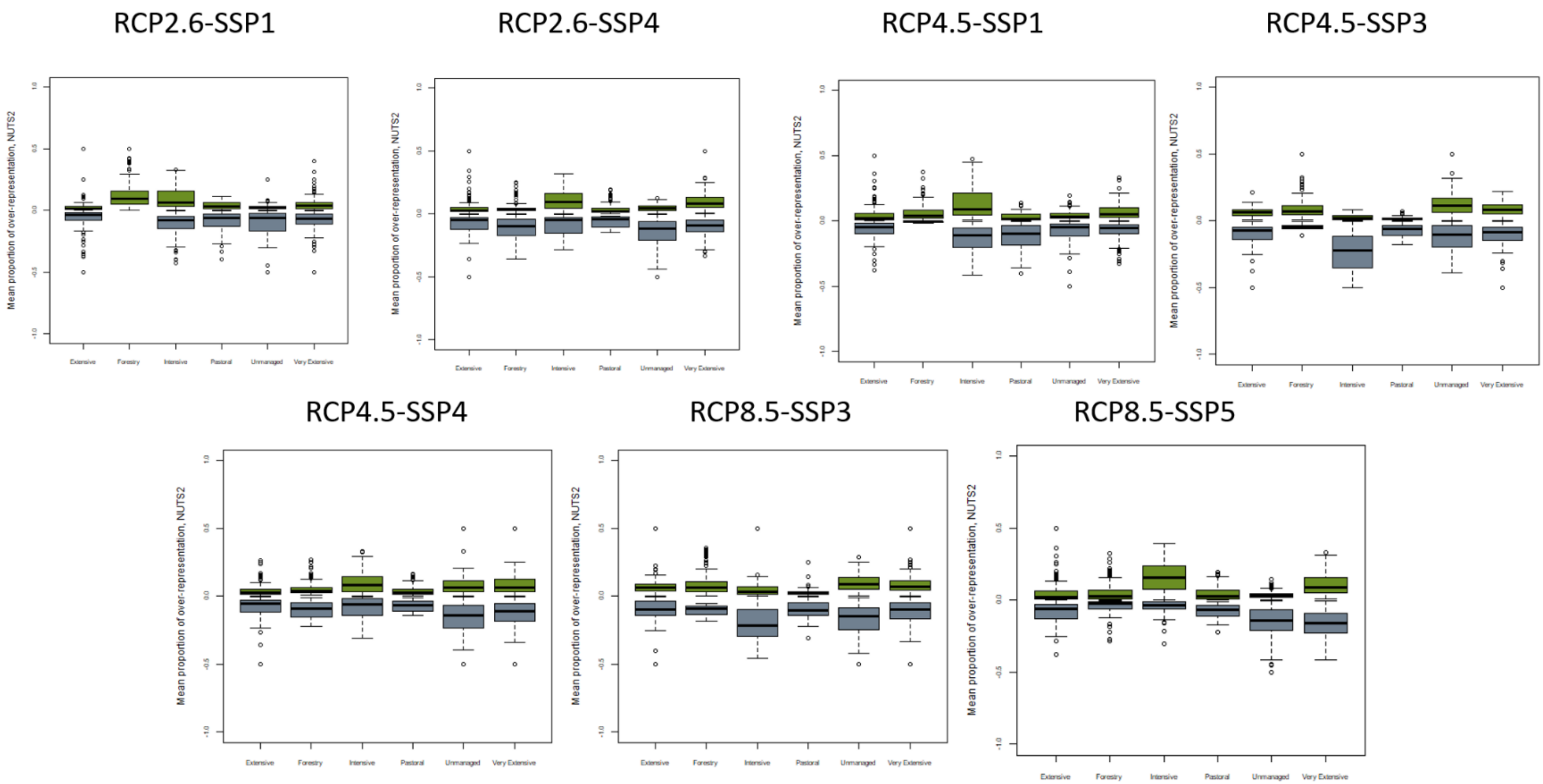


Figure 13: The most substantially over-represented land use types across European NUTS2 regions for each scenario. Green boxes show the mean over-representation of each type by CRAFTY-EU (compared to the IAP2), and the grey boxes show the mean over-representation of each type by the IAP2 (compared to CRAFTY-EU). Order of land use types on the x-axis is Extensive, Forestry, Intensive, Pastoral, Unmanaged, and Very extensive.

3.5. Population and urban growth

3.5.1. Inter-model comparison

A range of datasets and models were used in IMPRESSIONS to reflect changes in population and/or urban growth across different spatial scales. These include:

(i) Global-scale datasets on population change related to the SSPs (Jones & O'Neill, 2016);
(ii) European-scale datasets for population produced by Terämä et al. (2017) for IMPRESSIONS (see Deliverable D3C.1 [Rounsevell et al., 2015] section 2.3);
(iii) European-scale model outputs for both population and urban area from the IAP2 for Europe developed for IMPRESSIONS. In the IAP2, the Regional Urban Growth model version 2 (RUG2) is used to allocate population and urban area in future scenarios;
(iv) European-scale model outputs for both population and urban area from the Regional Integrated Assessment Model (rIAM) for Europe developed within IMPRESSIONS. The Regional Urban Growth model version 3 (RUG3) was used to allocate population and urban area in future scenarios.
(v) Regional-scale model outputs for both population and urban area from the IAP2 for Scotland (based on RUG2), developed in IMPRESSIONS;
(vi) Regional-scale model outputs for both population and urban area from the ALLOCATION model developed for Hungary in IMPRESSIONS (Li et al., 2016; 2017).

More detailed model descriptions are given below.

<u>3.5.1.1 NUTS2 downscaled European population</u>

The Wittgenstein Centre (2015) holds the most recent version of the population component of the SSP database, which provides the fundamental socio-economic datasets for the IPCC process (IIASA, 2012). These datasets include population by age, sex and education; patterns of urbanisation; and information on changes in GDP. Spatially, the data are available only at a national scale. As such, there is a need to downscale these data to a finer spatial resolution to enable it to act as inputs to the modelling within IMPRESSIONS. To address this, Terämä et al. (2017) downscaled the age-specific national population projections to spatially-explicit, sub-national administrative data at the NUTS2 level using data from Eurostat.

To do this, the downscaling process made two key assumptions. First, it was assumed that the national level distribution of population by age range (from the SSPs) was constant across all national sub-units (i.e. the NUTS2 units had the same distribution as the national). Second, it was assumed that no sub-national migration took place between units. Using these two assumptions, the national-scale Wittgenstein data were applied to the NUTS2 age-pyramids from Eurostat to reflect changing population for the future SSP scenarios for 10-year time steps for the period of 2010-2100. These data were used as an input to the modelling in rIAM and ALLOCATION. In the analysis below, the Terämä et al. (2017) data were used as the reference for population data against which other datasets were compared due to the fact that it is expected to be the closest representation of the SSPs.

<u>3.5.1.2 Global SSP-related population data</u>

Jones & O'Neil (2016) produced a second spatially-explicit dataset on population for the SSPs. However, they (i) focus on changes at a global scale; (ii) use a grid-cell based approach at a 1/8^{o} spatial resolution (rather than NUTS2); (iii) use a gravity-based model that uses potential urban and rural attractiveness to allocate population change and (iv) extrapolate from different baseline data (2.5' gridded world population dataset for the year 2000 from CIESIN [2005] rather than Eurostat data). For more details, see Jones & O'Neil (2016).

3.5.1.3 IAP2 Rural Urban Growth version 2 (RUG2) model (used for both Europe and Scotland)

The original RUG model (Reginster & Rounsevell, 2006; Rickesbusch et al., 2010) simulates urban growth as a function of changes in socio-economics and societal preferences. The full model takes into consideration local geography, travel times with existing infrastructure and city type (mono- or poly-centric). However, the run-time of the full model is too long to be included in the online, interactive IAP2 and therefore a simplified meta-model was embedded within the IAP2.

The RUG2 meta-model is embedded within both the European and Scottish versions of the IAP2. Like the Terämä et al. (2017) data, the RUG1 model is focussed on the European/national scale rather than the global (as with Jones & O'Neil, 2016), and the model allocates urban area and population differently. The main differences from the Terämä et al. (2017) data are: (i) the RUG2 meta-model used within the IAP2 is a look-up-table based on the 1 km x 1 km outputs of this model summarised to the appropriate resolution (e.g. at a 10' x 10' grid for Europe and a 5 km x 5 km grid for Scotland, rather than NUTS2 and (ii) RUG2 is a regression model (Reginster & Rounsevell, 2006) driven by population, GDP/capita, urban area type (large city/rural region) and country. The model takes into consideration factors such as scenario-driven preferences for urban growth, such as the desire to live within proximity of the coast or for rural locations, and preferences for constraining urban sprawl, which are IAP2 scenario inputs.

3.5.1.4 The Regional Integrated Assessment Model (rIAM, used for Europe)

The Regional Integrated Assessment Model has been developed within IMPRESSIONS. The RUG version 3 model within rIAM is based on the RUG2 model within IAP2, but expanded to (i) consider time dependency between scenarios to allow it to run on 10-yearly time steps between 2010 and 2100 with each time step building on the urban extent of the previous time step, and, in addition (ii) it is customised to the SSP scenarios in a way that the original RUG model is not; it considers a greater level of detail in terms of population characterisation and considers the age structure of the population. It does this by using the spatially downscaled NUTS 2 population data from Terämä et al. (2017) as an input.

3.5.1.5 The ALLOCATION model (used for Hungary)

ALLOCATION is a new grid-cell based spatial model developed specifically for the IMPRESSIONS Hungarian case study. It uses linear regression functions to project demand for urban development based on NUTS2 level inputs from Terämä et al. (2017). These NUTS2 level demands are then distributed to 1km^2 cells and the expected cell-level increase of each land class is then estimated. This estimation is a function of the cell development potential based on (i) accessibility and landscape configuration; (ii) policy preferences for certain land classes (e.g. commercial/industrial) in particular regions; and (iii) policy/societal preferences for compact or sprawling urban settlements. The impact of climatic change is modelled through its projected relationship with GDP. Modifying these factors by scenario allows the Hungarian case study to assess the influence of economy, climate, demographics, residential preferences and urban planning.

3.5.2. Results

For each dataset, values were compared for the baseline and for each of the four SSPs at the most appropriate comparable spatial resolution. For European datasets, the NUTS2 level was used to compare all datasets (IAP2 Europe and Scotland, rIAM, Jones and O'Neil and the spatially downscaled Terämä et al. data). The official SSP quantifications from the IIASA website downscaled by Terämä et al. (2017) were used as a reference against which the other models were compared. In addition, the IAP2 and rIAM datasets were also compared at the 10' x 10' grid-cell level (for cells shared by both models). All SSP comparisons are for the same time period 2080-2100, while baseline comparisons are for *circa* 2010.

<u>3.5.2.1 Comparison for baseline</u>

When aggregated to a NUTS2 level all datasets have a relatively high correlation with the baseline data used by Terämä et al. (2017) (Figure 14). The global and European datasets plot very close to the 1:1 line illustrating their close match with the Terämä et al. (2017) data. The regression lines diverge slightly for regions with higher population within the Terämä et al. (2017) data with the IAP2 deviating above the line and rIAM and Jones and O'Neil (2016) datasets deviating below the line. The rIAM data are the closest to the line reflecting the fact that the Terämä et al. (2017) data were used to train the modelling within rIAM, which was not the case for either the IAP2 data (pre-dating the SSPs), which was trained on CORINE land cover data, nor for the Jones and O'Neil (2016) data, which were trained on CIESIN data from 2010 (see above). Nonetheless, all lines show very highly statistically significant correlations (R^2 between 0.85 and 0.97) with the trends in population used by Terämä et al. (2017). Scottish and Hungarian modelling for baseline also shows a high level of correlation with the other models, plotting very close to the regression lines for the other models.

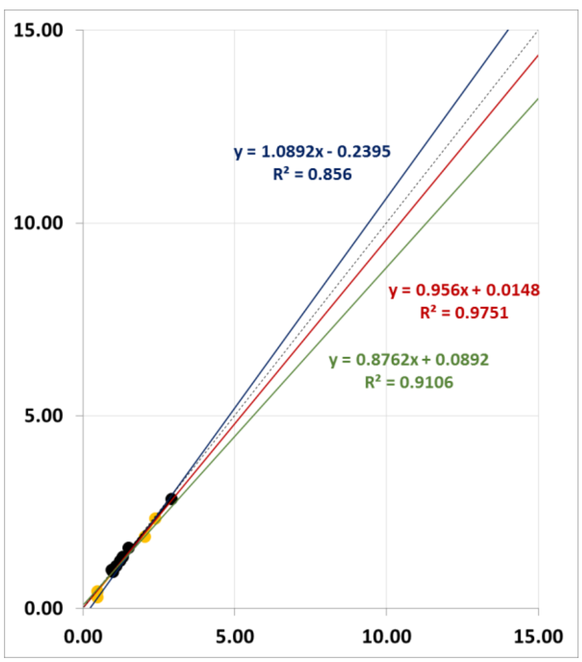


Figure 14: NUTS2-level comparison of population (million people per NUTS2 region) showing regression lines for IAP2 Europe (blue line), Jones & O'Neil data (green) and rIAM (red) and aggregate raw data for IAP2 Scotland (gold dots) and Hungary (black dots) relative to IIASA baseline data for Europe. Dashed line is 1:1 line with IIASA data.

Looking in more detail at the scatter plots for the European-scale models (Figure 15 a-c) it is clear that there are more outliers in the IAP2 data, particularly above the line, the clearest of which is the Isle de France region of France (FR10). This region has a greater population in the IAP2 modelling than in the Wittgenstein NUTS2 downscaled data. Of the three models, the rIAM data, which is trained on the Terämä et al. (2017) data, has the greatest correlation ($R^2 = 0.97$). This similarity is also apparent in the mapped data (Figure 15 d-f) with fewer NUTS2 regions in the rIAM data showing values > +/- 10% from the Terämä et al. (2017) data. The maps reveal some commonalities in spatial patterns. In general, Scandinavia and Western Europe show values lower than the downscaled Terämä et al. (2017) values, while Eastern Europe and some parts of Central Europe and the UK show higher values than Terämä et al. (2017).

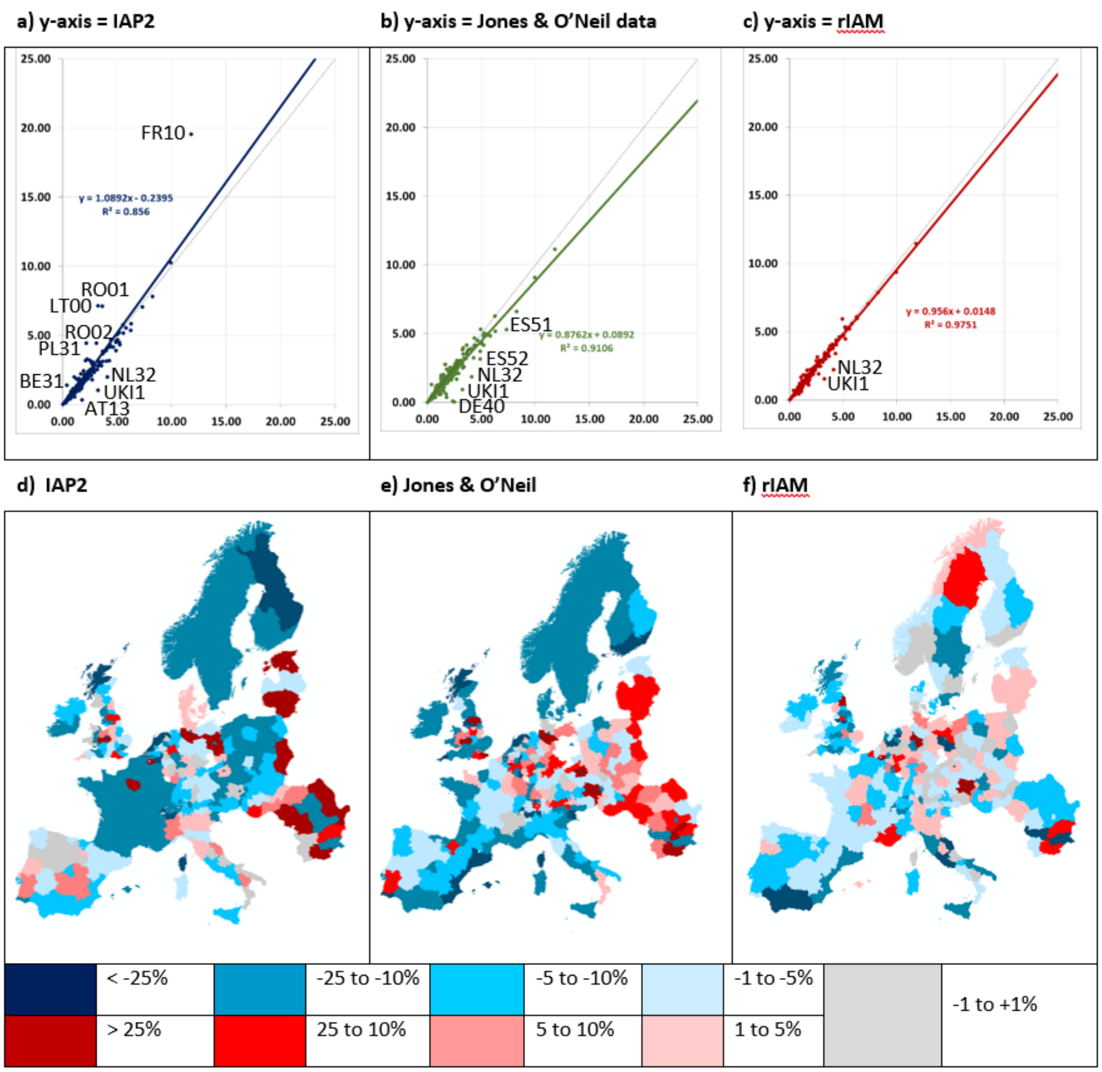


Figure 15 a-c: Differences between model outputs and IIASA population data at baseline at the NUTS2 scale. Some key outliers are labelled with their NUTS2 code: FR10 = Ile de France; RO01 = North-west Romania; LT00 = Lithuania; RO02 = South-east Romania; PL31 = Lublin, Poland; BE31 = Walloon Brabant, Belgium; NL32 = North Holland, the Netherlands; UKI1 = Inner London, England; AT13 = Vienna; ES51 = Catalonia, Spain; ES52 = Valencia Community, Spain and DE40 = Brandenburg, Germany. d-f: relative change from Terämä et al. (2017) NUTS2-scale data by model.

Figure 16 shows the relationships between the rIAM and IAP2 datasets at the 10' x 10' resolution at which they are both generated. The correlation between the IAP2 data and rIAM data for population is quite good (R^2 =0.75). Although the deviation between the two models may be minor for a grid cell, the low values of urban area and population make the proportion of the relative differences highly visible. Moreover, there are very few grid cells where population is allocated similarly between the two models (Figure 16 c-d). A visual comparison of the spatial patterns reveals that IAP2 and rIAM have the greatest amount of agreement in terms of area with changes <+/-1% in areas with very low population (e.g. Fennoscandia, Northern Scotland and areas of Spain).

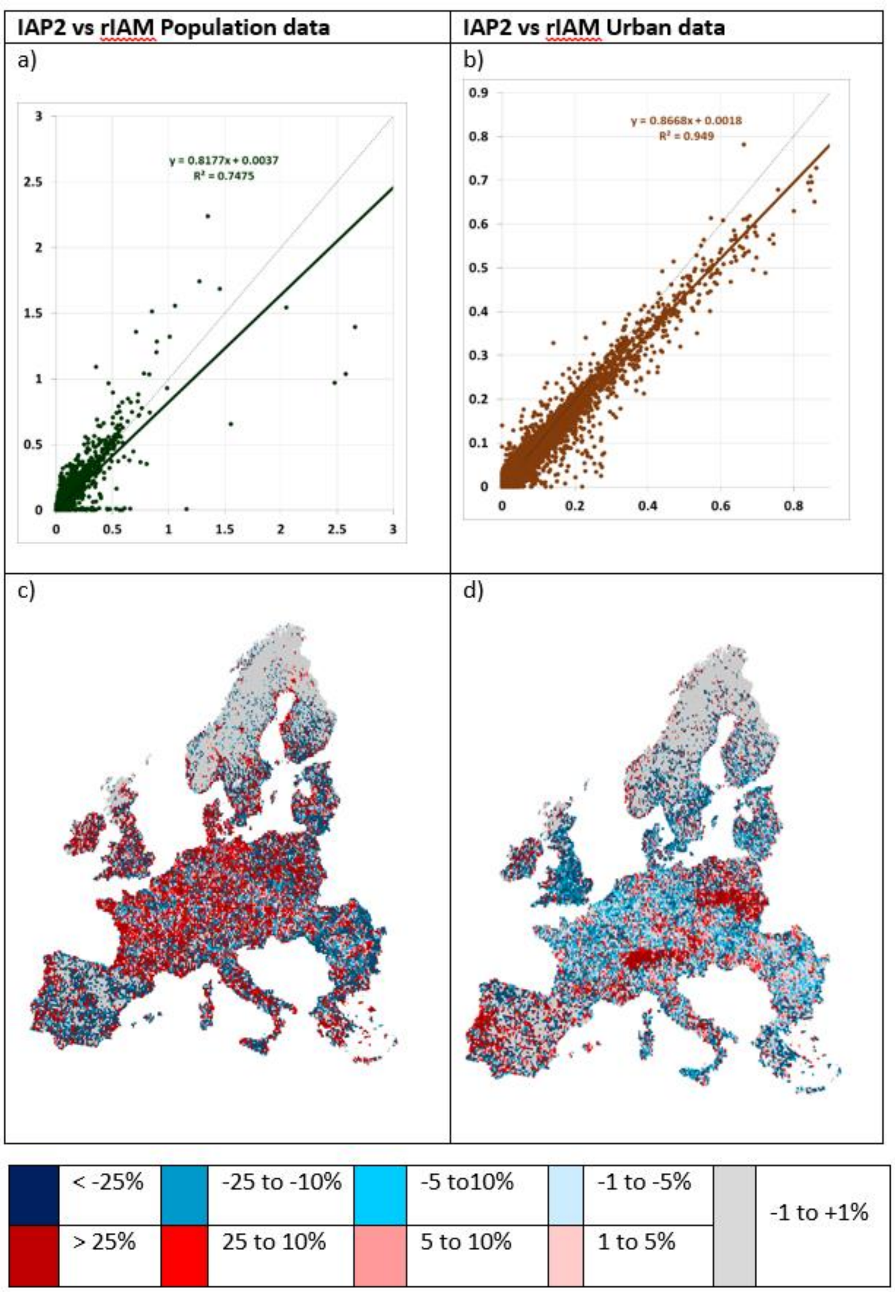


Figure 16 a-b: Scatterplots and c-d: Maps highlighting percentage difference between rIAM and IAP2 datasets for baseline at the 10' x 10' resolution for population (a-c) and urban area (b-d).

Differences in urban areas show clearer patterns outside of the areas where there is very little population, with rIAM projecting higher values around the Alps (particularly Switzerland and Austria), on the Iberian peninsula (particularly in the West), in Ireland and in central Poland. Conversely, the IAP2 projects higher values particularly in the UK, Scandinavia, Greece, Latvia and Estonia. These differences in both urban area and population datasets can be explained by the different modelling approaches. For example, rIAM downscales population data from national to NUTS 2 data whereas the IAP2 data is projected from regressions based primarily on GDP and population.

3.5.2.2 Comparison for scenarios for Europe

There are relatively high correlations (R^2 values between 0.70 and 0.90) between the different projections of population at the NUTS2 level in the different scenarios (Figure 17). The rIAM model trained on the Terämä et al. (2017) data shows the highest correlations (ca. > 0.87 in all scenarios); the Jones and O'Neil data (2016) varies between R^2 of 0.85 and 0.86, while the IAP2 data shows the lowest correlation ranging from R^2 of 0.70 to 0.80. Furthermore, while the rIAM and Jones and O'Neil (2016) data project values consistently below and above the lines (respectively), the IAP2 shows different trends depending on the scenario in question, with a trend higher than the Terämä et al. (2017) data in SSP3 and SSP4, and lower in SSP1 and SSP5. Hungary and Scotland plot very close to the 1:1 line in most scenarios, except in SSP5 where the Scottish data plots considerably below the line.

A comparison of the IAP2 and rIAM outputs for urban area and population growth at the 10' grid scale shows that there are considerable differences in the spatial patterns between the two models (Figure 18). The rIAM data, based on the Terämä et al. (2017) data, shows considerably greater population across much of Western Europe and considerably lower population in Eastern Europe in a way that reflects overall patterns of change in SSP populations. This reflects the fact that the IAP2 does not target population at a national scale in the same way as rIAM. The rIAM has pre-defined levels of population for each country from the Wittgenstein (2015) SSP data. Conversely, the IAP2 projects urban area and population change based on variables such as GDP and total population change at the European scale, and has no knowledge of how these are projected to be allocated differentially between countries.

3.5.2.3 Comparison for scenarios for Scotland

Two models are available for Scotland – the Scottish and European versions of the IAP2 (Figure 19). The comparison below highlights that the models follow similar trajectories with high levels of correlation for both population and urban area ($R^2 > 0.95$), but that despite this, there are notable differences in the spatial pattern, which results from significant deviations from the 1:1 line. This is only the case for populated regions, as for large areas of Scotland with low populations there is very little difference between the two models (both project very low population). For more populated areas, baseline and SSP3 (where population change is none or negative) show a mix of under- and over-predictions with no clear pattern. In SSPs 1, 4 and 5, however, the Scottish version of the IAP2 projects a greater population in most areas. The visible deviation of the results of the Scottish IAP2 from that of the European IAP2 is due to the values of population and urban area being small.

3.5.2.4 Comparison for scenarios for Hungary

The comparison between IAP2 and the ALLOCATION model (Figure 20) shows high correlations between the two models for both population and urban area data at baseline ($R^2 > 0.91$) and in all scenarios ($R^2 > 0.87$). The majority of regression lines also plot very close to the 1:1 line, showing that the models not only correlate, but show generally similar values. However, in SSP3 and SSP4 there are highly correlated trends with notable differences from the 1:1 line in the population data, despite relatively strong correlations close to the 1:1 lines in terms of urban area. A closer examination of all regression lines reveals that while extreme areas of high population project close to the regression line, there are notable differences at the low-population end, with ALLOCATION often projecting higher values than the IAP2 in the baseline, SSP1 and SSP5, but lower in SSP3 and SSP4. This is seen in the considerably lower values across the majority of Hungary in SSP3/4. These differences are likely to reflect the differences in modelling approaches used between the two models with the IAP2 population allocated in consideration of changes across the whole of Europe, while the Hungarian data is trained based on SSP-specific changes projected for Hungary itself.

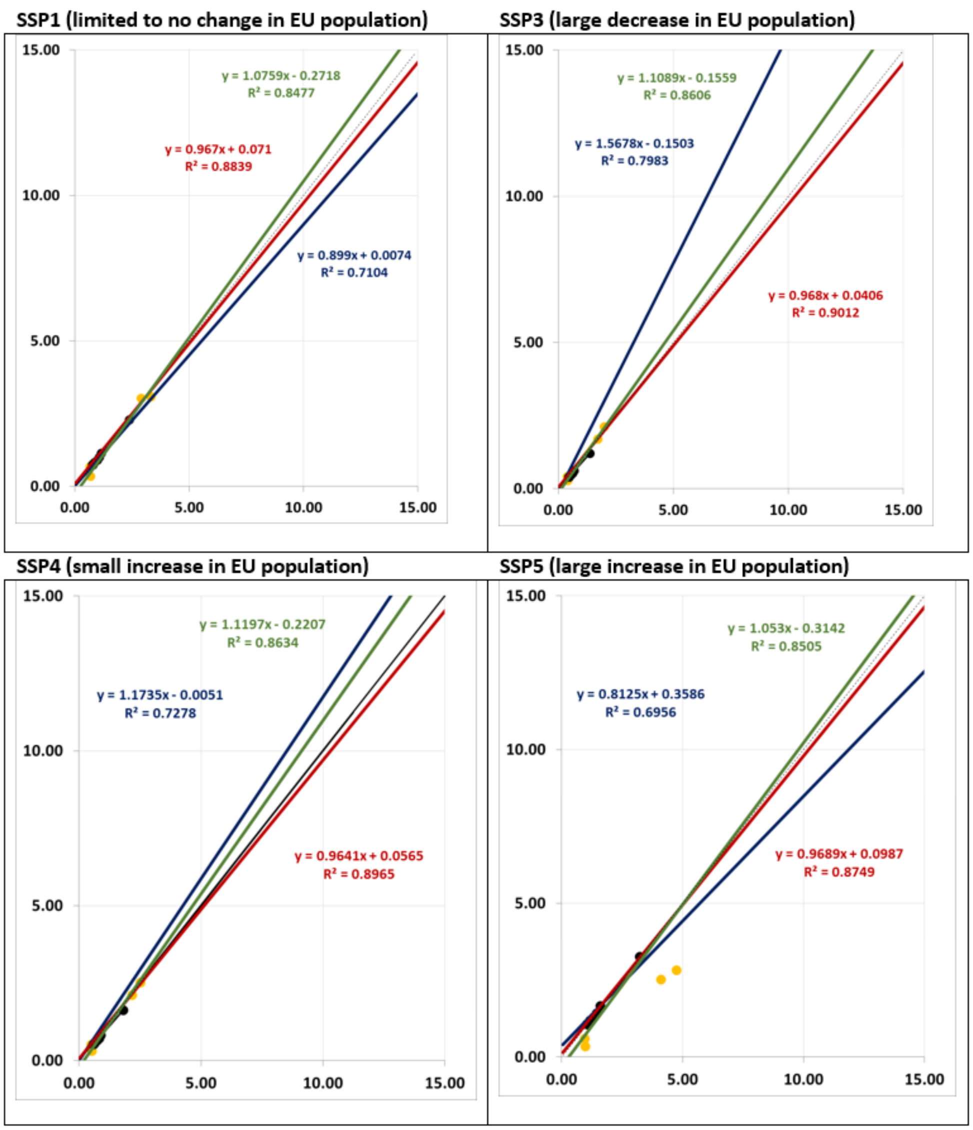


Figure 17: NUTS2-level comparison of population (million people per NUTS2 region) showing regression lines for IAP2 Europe (blue line), Jones & O'Neil (2016) data (green) and rIAM (red) and aggregate raw data for IAP2 Scotland (gold dots) and Hungary (black dots) relative to IIASA SSP scenarios data for Europe. Dashed line is 1:1 line with IIASA data. Descriptive change in population in brackets after SSP label is for the 2080-2100 time period.

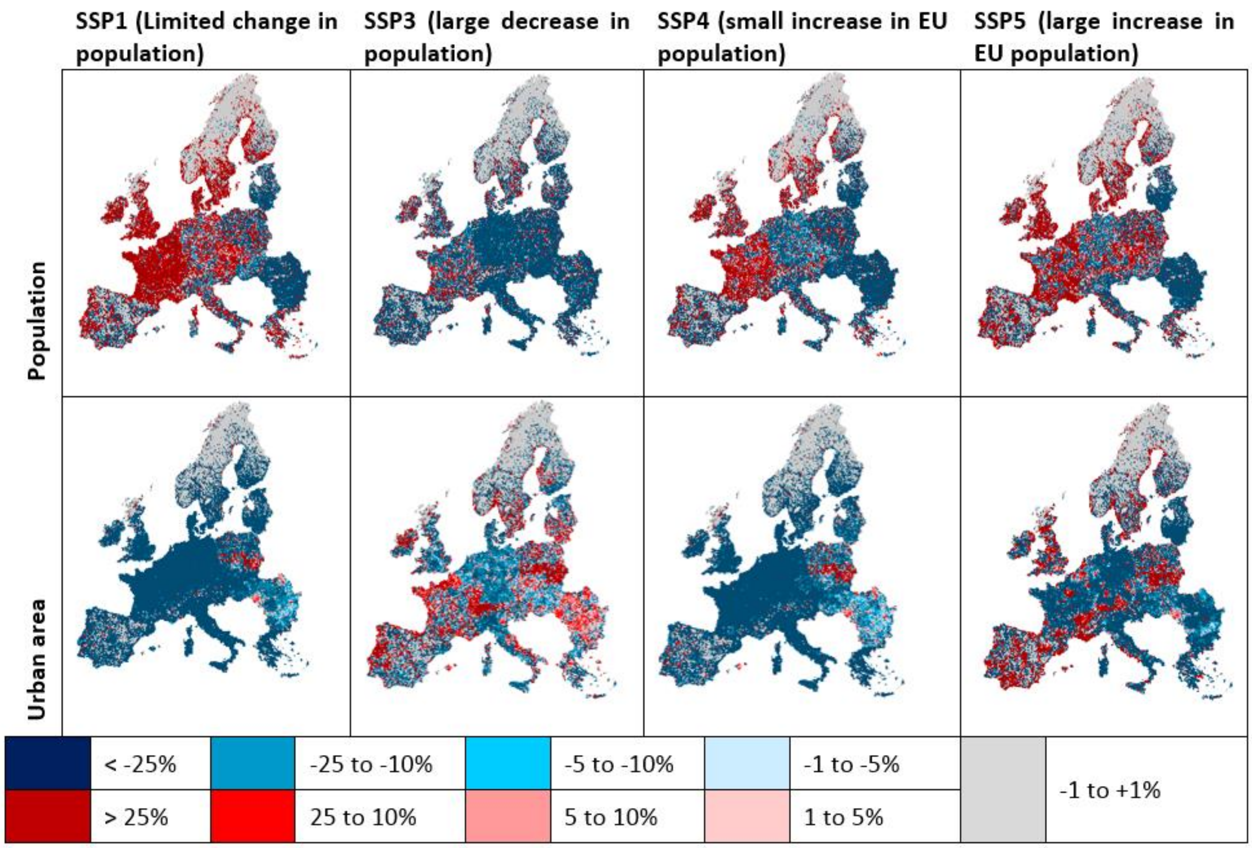


Figure 18: Spatial patterns of the percentage difference between rIAM and IAP2 datasets at the 10' by 10' grid cell resolution for both population and urban area for the four SSP scenarios used within IMPRESSIONS.

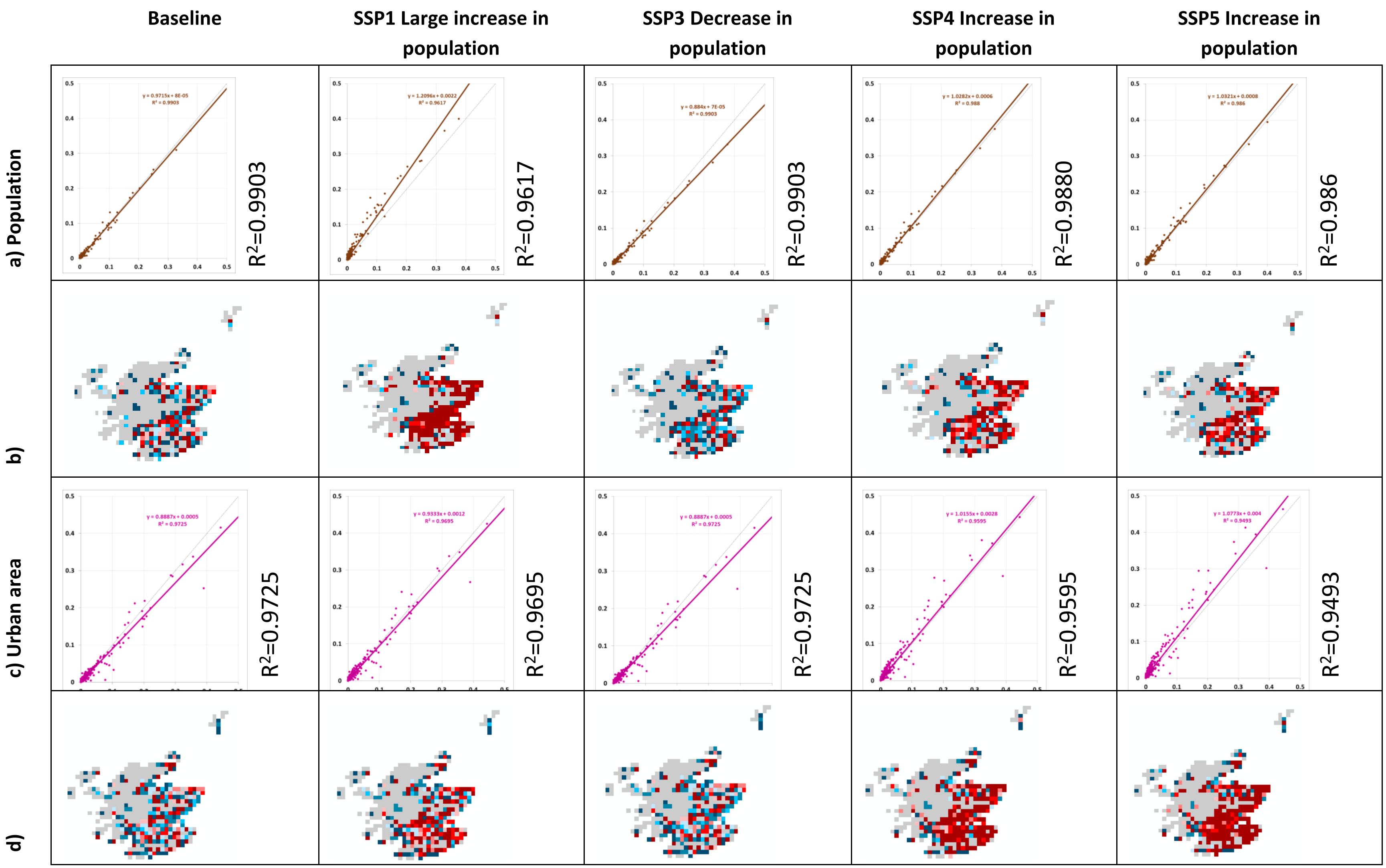


Figure 19: Scatterplots of a: population and c: urban area (x-axis EU IAP2; y=Scottish IAP2), and maps highlighting the percentage difference in b: population and d: urban area between the Scottish IAP2 and European IAP2, at baseline and for the SSPs. The Scottish IAP2 results are aggregated to the resolution (10') of the EU IAP2. The key for the rows b) and d) is the same as for Figure 18. Reds show Scottish IAP2 > European IAP2; Blue shows the inverse.

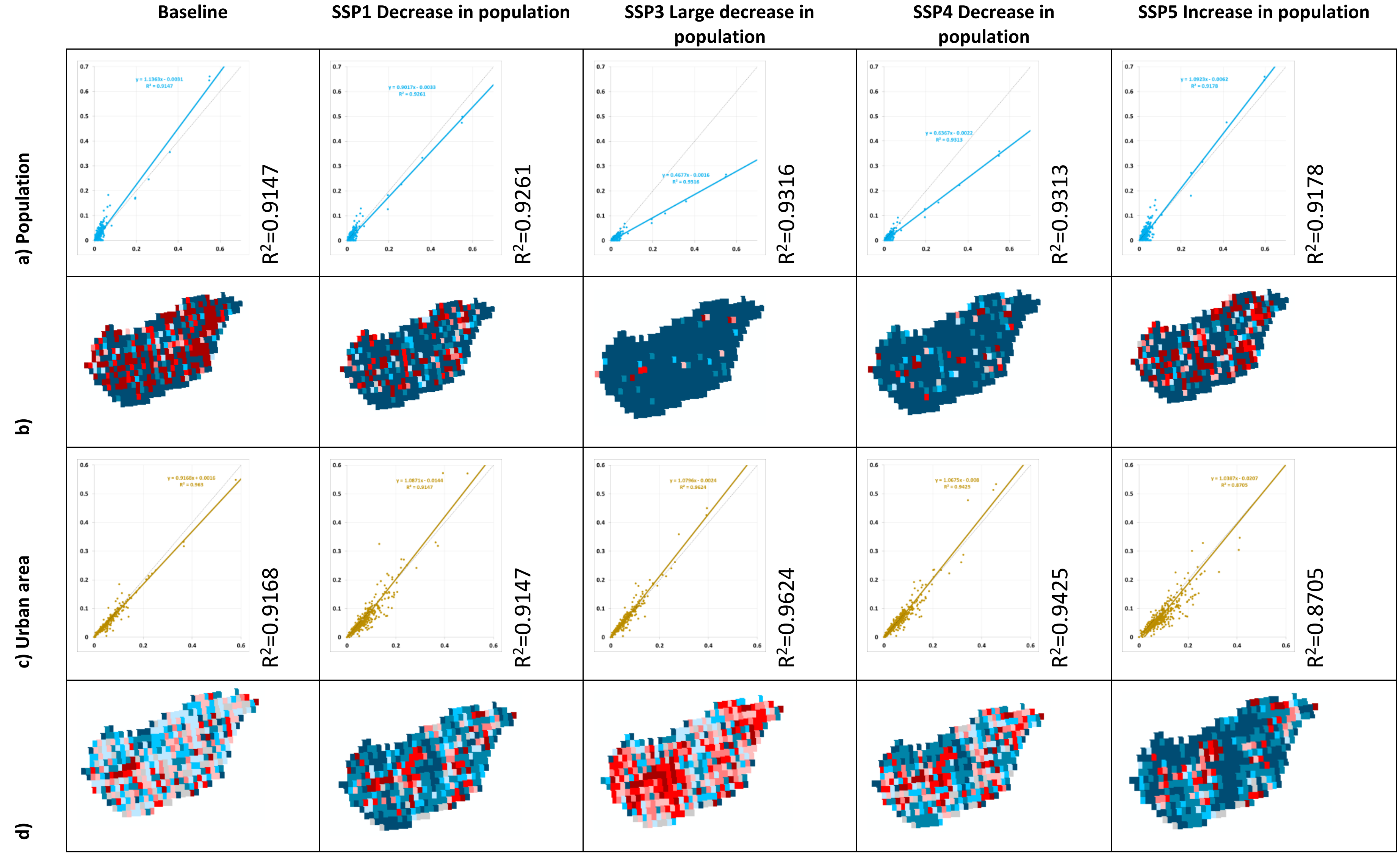


Figure 20: Scatterplots of a: population and c: urban area (x-axis EU IAP2; y=Hungarian ALLOCATION), and maps highlighting the percentage difference in b: population and d: urban area between the ALLOCATION and European IAP2 models, at baseline and for the SSPs at the scale of the European versions of IAP2. The key for the rows b) and d) is the same as for Figure 18. Reds show ALLOCATION>IAP2; Blue shows the inverse.

4. Inter-model and cross-scale comparisons using impact response surfaces

Responses to future changes in climatic and socio-economic conditions can be expected to vary between sectors and regions, reflecting differential sensitivity to these highly uncertain factors. A sensitivity analysis was conducted using a suite of IMPRESSIONS impact models (for health, agriculture, biodiversity, land use, floods and forestry) across Europe with respect to changes in key climate and socio-economic variables (Fronzek et al., in review). Results were aggregated to eight European sub-regions (see Figure 1) and plotted as scenario-neutral impact response surfaces (IRS). These depict the modelled behaviour of an impact variable in response to changes in two key explanatory variables.

The sensitivity analyses of the models were conducted for at least two input variables (climate-related and/or socio-economic) such that these variables were perturbed simultaneously over ranges defined to be wide enough to encompass projections of long-term changes for the 21st century that plausibly could occur somewhere in Europe. Aggregated model results were plotted as contoured IRS with respect to the axes of the two drivers. A summary of results from the sensitivity analyses to climate change is presented here; more details as well as sensitivity analyses to socio-economic variables are presented in Fronzek et al. (in review).

IRS for changes relative to the baseline for impact variables relevant to agriculture (i.e. crop yield, net primary production – NPP, mean river discharge and intensive agricultural land use) showed general increases in these impact variables as precipitation increased, and decreases as temperature increased (Figure 21).

The patterns of yield response of the three crop species showed large regional variation. Regional changes in NPP showed smaller differences between the eight sub-regions compared to the crop yield IRS, suggesting that the local adaptation of natural ecosystems shares characteristics regardless of the prevailing regional climate. Changes in mean river discharge were mainly affected by changes in precipitation, with decreasing precipitation reducing river flows. Although the European regions differed little in the shape of their IRS, the strength of the precipitation response varied across Europe. Changes in the proportion of intensive agricultural land use decreased for increases in precipitation and temperature in all regions except Central Europe. The decreases coincided with increases in crop yields in most regions, especially the Iberian Peninsula, France and Mediterranean (Figure 21).

The stem basal area of the five simulated tree species increased under wetter conditions in all regions, whereas the temperature optimum varied between region and species (Figure 22). Distinct temperature and precipitation thresholds can be identified from the IRS, for example a sharp decline in basal area can be seen for European beech and Sessile oak in the British Isles for warming of 6°C or more. For European beech, Sessile oak and Scots pine in the Alps, a clear threshold was found for precipitation decreases of more than 20%. Large increases in basal area of more than 40 m^2 ha^{-1} were simulated for several locations at their respective optimum perturbation.

The percentage of forest land use increased for wetter and decreased for drier conditions for most regions, except in Central Europe, where decreases were simulated for nearly all perturbations (Figure 22). The patterns of changes were largely opposite to those of intensive agricultural land use (see Figure 21).

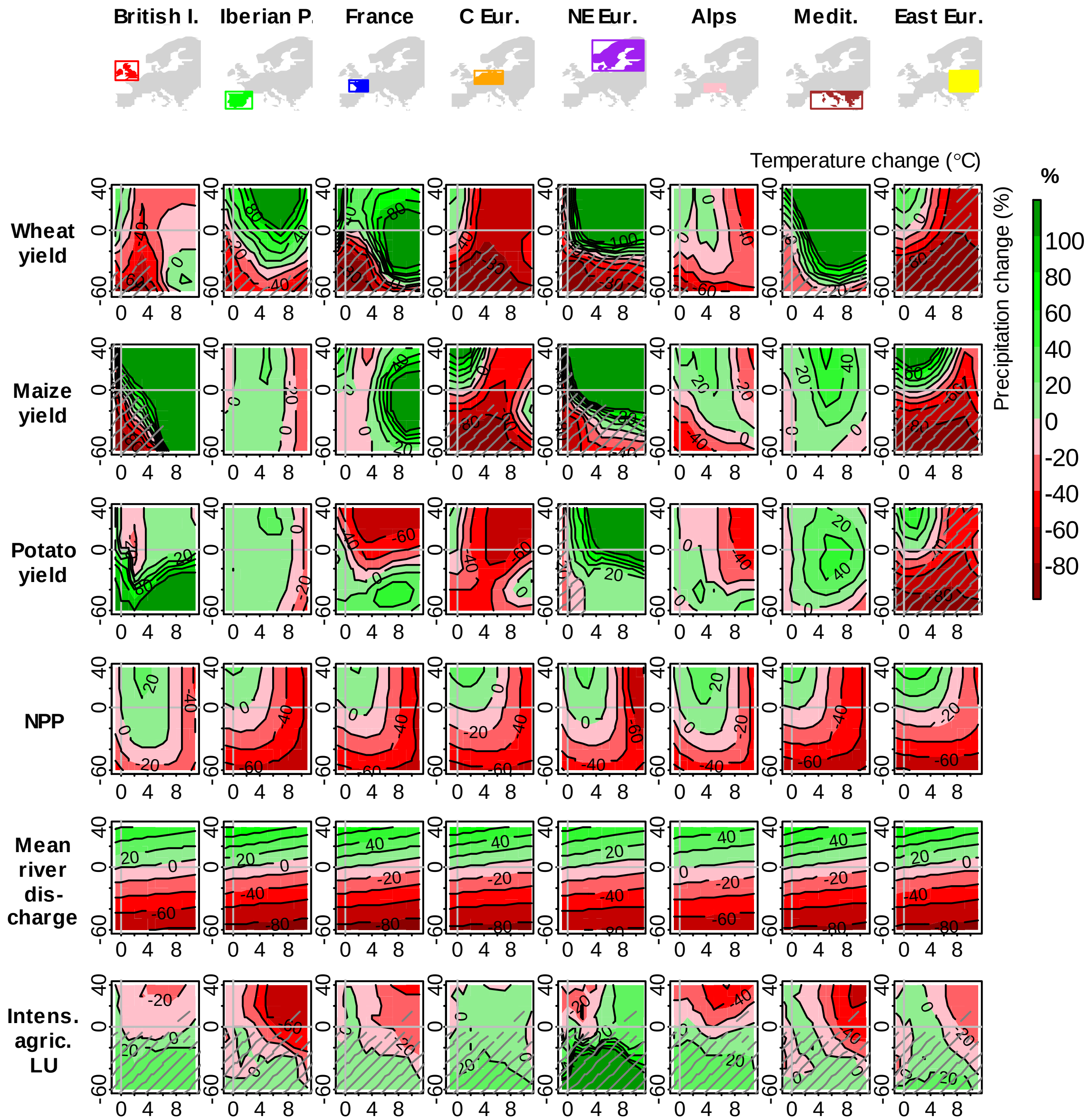


Figure 21: Example of impact response surfaces of variables relevant for agriculture and their sensitivity to changes in mean annual temperature (x-axis in °C) and precipitation (y-axis in %). From top to bottom rows: change in wheat, maize and potato yields, change in net primary production (NPP), change in mean river discharge and change in intensive agricultural land use (LU). All simulations are without the CO_2 effect and technological development. Hatched areas denote crop yields below 1000 kgha^{-1} and European demand not being met for intensive agricultural land use (Fronzek et al., in review).

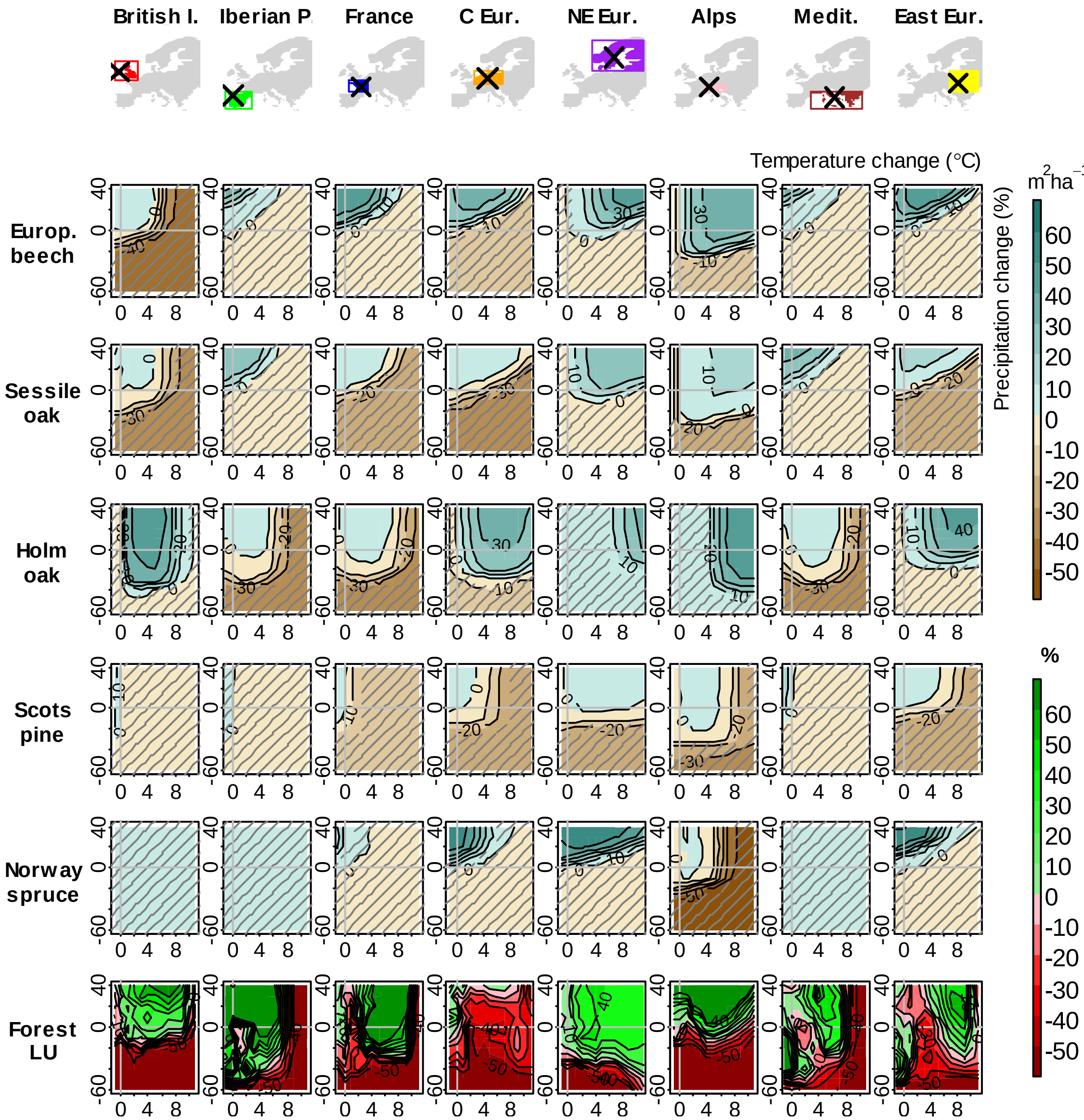


Figure 22: Impact response surfaces of variables related to forestry and their sensitivity to changes in mean annual temperature and precipitation. From top to bottom rows: change in basal area of European beech, Sessile oak, Holm oak, Scots pine and Norway spruce (absolute change in m^2 ha^{-1}) and change in forest land use (LU) (relative change in %). Hatching shows impact outcomes that are not economically viable (basal area < 2 m^2 ha^{-1}). Black crosses on maps above the columns indicate the grid cell locations for forest basal area simulations (Fronzek et al., in review).

The sensitivity to changes in precipitation and temperature was estimated as the average rate of change per 10% precipitation change and per 1°C temperature change (Fronzek et al., in review). To ensure that the climate changes considered were consistent with model projections for a given region, these were calculated only for perturbations over that portion of an IRS encompassing the 5th to 95th percentiles of 21st century CMIP5[1] global climate model (GCM) projections for “high-end” RCP8.5 forcing. We used a sub-set of 38 projections (van Oldenborgh et al., 2013) to calculate period-averaged changes in annual mean temperature and precipitation for the land grid cells of the eight regions. Portions of the IRS that were analysed therefore differed slightly between regions. For the same sub-set of impact indicators, the IRS were also used to estimate impacts of the 38 GCM projections. These were calculated from the IRS by interpolating to the locations of perturbations corresponding to each climate projection.

An attempt to summarise the sensitivity of the climate-driven impact indicators shown by their IRS is given in Figure 23. This plots the median sensitivity to temperature and precipitation changes by region across all indicators (coloured points) and by indicator across all regions (black symbols). For the set of impact indicators considered, the British Isles was the region with the smallest sensitivity to both temperature and precipitation (across all indicators), whereas Central Europe had the strongest median response to temperature and Eastern Europe to precipitation. The Iberian Peninsula had the largest precipitation-to-temperature sensitivity ratio, implying a relatively stronger response to precipitation than temperature compared to other regions. The British Isles showed the lowest ratio.

The median sensitivity to temperature of indicators across the regions was lowest for the two river discharge indicators and highest for the basal area of Norway spruce (Figure 23). At the low-end of sensitivity to precipitation were intensive agricultural land use, maize and potato yields and the basal area of Scots pine, whereas the largest precipitation sensitivity was found for Norway spruce. For crop yields, wheat was around three times more sensitive to precipitation than potato and maize. Similarly, the two land use indicators showed contrasting sensitivities with forest land use being more sensitive to precipitation than agricultural land use.

The variation of sensitivities across individual indicators and regions is large for most indicators (not shown). Exceptions are the two river discharge indicators and, to a lesser extent net primary production (NPP) and agricultural land use, whose regional values clustered around a small range of sensitivities both for temperature and precipitation.

To complement the results on sensitivity across the IRS, Figure 24 depicts averaged responses for each region and climate-driven impact indicator. Responses are medians across the 38 perturbations defined by the (high-end) CMIP5 RCP8.5 GCM projections for the end of the 21st century. North-eastern Europe showed increases in yields of all crops and basal area of all tree species, whereas Central and Eastern Europe showed decreases in these indicators (Figure 24). In regions of southern Europe (Iberian Peninsula, France and Mediterranean) indicators of river discharge and stem basal area (except Holm oak) were projected to decrease, whereas crop yields increased in these regions, where it was assumed that irrigation would compensate for decreases in precipitation.

[1] Coupled Model Inter-comparison Project Phase 5 (Taylor et al., 2012)

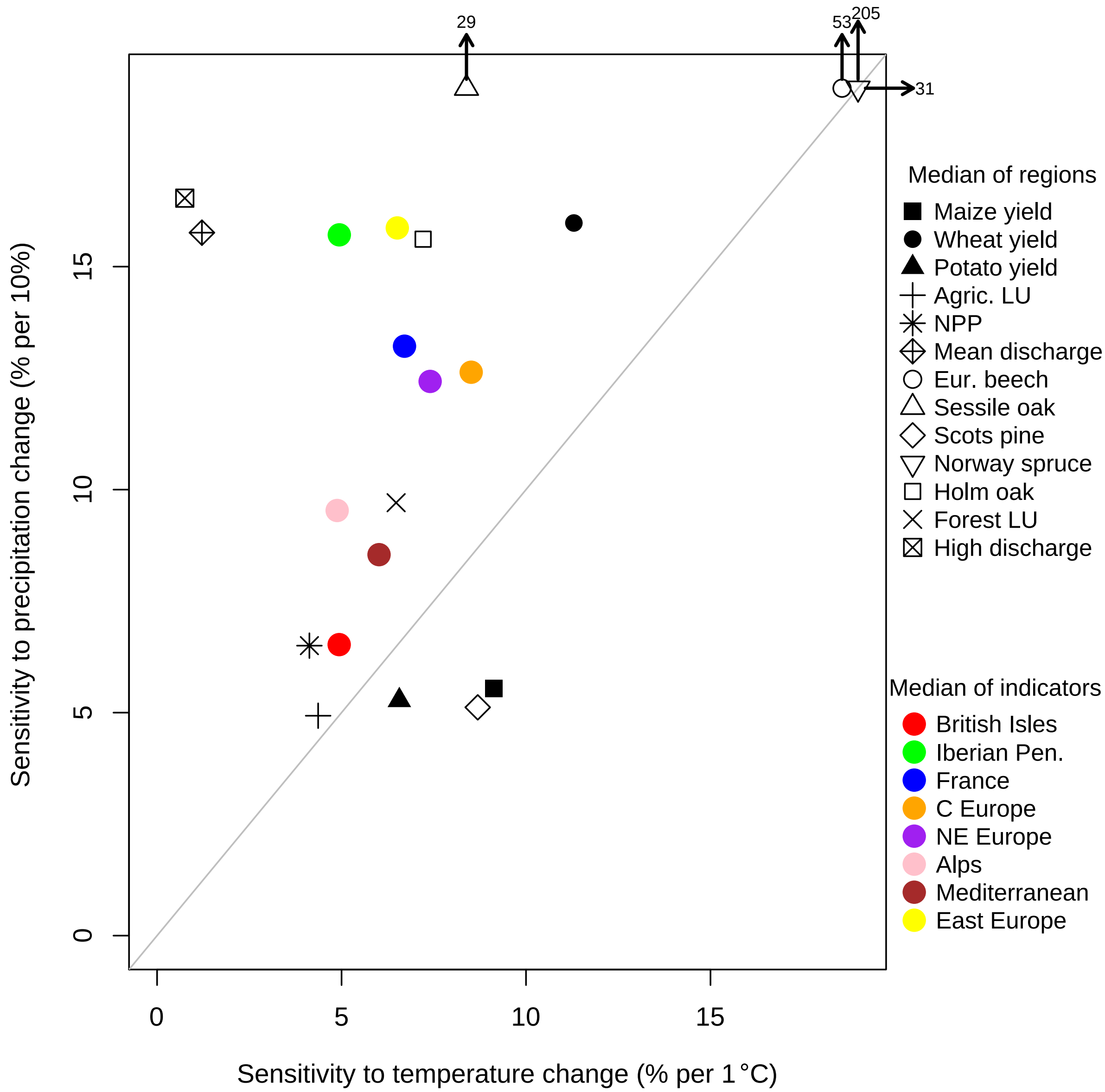


Figure 23: Sensitivity of 13 impact indicators to changes in temperature and precipitation averaged across ranges of perturbations defined for each region by 21st century CMIP5 RCP8.5 projections (see text). Coloured points show the medians across the indicators for each sub-region; symbols show medians across the eight regions for each indicator. Points to the right (left) of the grey line show a larger (smaller) relative change in the impact indicator per 10% precipitation change than per 1°C temperature change (Fronzek et al., in review).

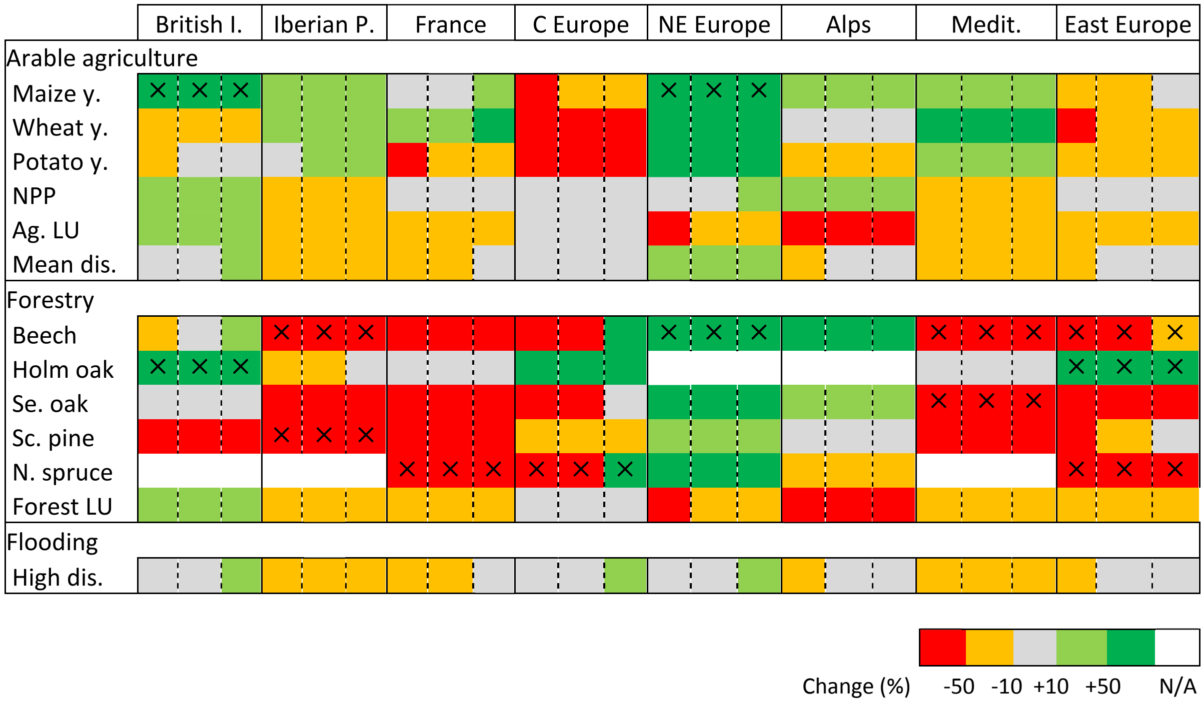


Figure 24: Simulated high-end climate change impacts on indicators of relevance to agriculture, forestry and flooding across eight European sub-regions. Impacts are for the period 2070-2099 relative to 1981-2010 based on 38 global climate models simulating the RCP8.5 forcing. Changes are in percent to enable comparison between indicators, and were derived from impact response surfaces plotted in original measurement units. Values are colour-coded in three adjacent cells for each indicator and region: from left to right, respectively, the 25th, 50th (median) and 75th percentile change. A cross indicates that baseline values of crop yield are below 1000 kg ha^{-1} or of stem basal area are below 2 m^{2} ha^{-1}. No value (N/A) is given if the baseline value is zero (Fronzek et al., in review).

5. Qualitative synthesis across case studies and models

5.1. Description of synthesis table

To facilitate a qualitative comparison of scenario impacts across case studies and models, synthesis tables were created to highlight directions and broad magnitude of change in impact indicators in Europe and the regional/local case studies. Synthesis tables were produced for four key sectors: land use (agricultural and urban area); crop yields (wheat, barley, maize); forestry (productivity); water (discharge, availability, flooding); and health and wellbeing (heat related mortality, Lyme disease). Data were provided from the model runs undertaken for Europe as well as each regional/local case study area. Where model data were not available for regional/local case study areas, the relevant spatial window of a European model was used. For the IAP2 modelling, the sub-regions that most closely correspond to the case studies were used; for heat stress mortality (HEET), the relevant NUTS2 regions were used. The source of the data is highlighted throughout.

Mean values of impact indicators for three separate time slices relative to baseline are shown as arrows in the synthesis tables (Tables 1 to 5), representing changes over time. These time slices are:

- Baseline period for climate: 1981-2010 (only the year 2010 for socio-economic change)
- First time slice: 2010-2040 (~2020s)
- Second time slice: 2040-2070 (~2050s)
- Third time slice: 2070-2100 (~2080s)

The ranges shown in the cells of the synthesis tables reflect the approximate minimum and maximum values across the case studies for a specific indicator, aiding comparison across the different scales of the case studies. Where available and feasible, the data from different models is portrayed as different coloured arrows within the same diagram to highlight differences and similarities.

The background colour in the cells of the synthesis tables reflects the magnitude of decreases or increases in relation to the baseline. Impact magnitude was determined using percentiles with the midpoint set to zero. Hence, decreases in an impact indicator relative to baseline are in shades of red, while increases relative to baseline are in shades of blue. The stronger the shade, the stronger the impact. It should be noted that the colour does not reflect the potential benefit or dis-benefit of an impact to society or the environment. Figure 25 presents a key for interpreting background colours across all synthesis tables.

	Percentile
	5
	25
	45
	Midpoint set to 0
	55
	75
	95

Figure 25: Colour key for synthesis tables. All synthesis tables have been colour coded in the same manner for consistency. Where suitable, changes in indicators are compared to each other.

The results for four RCP x SSP integrated scenarios are displayed according to the matrix shown below (Figure 26). The output from the SWIM model is an exception, as it only has the climate (RCPs) as input, and accordingly only has two scenarios per time slice.

RCP8.5x SSP5	RCP8.5x SSP3
RCP4.5x SSP1	RCP4.5x SSP4

RCP4.5	RCP8.5

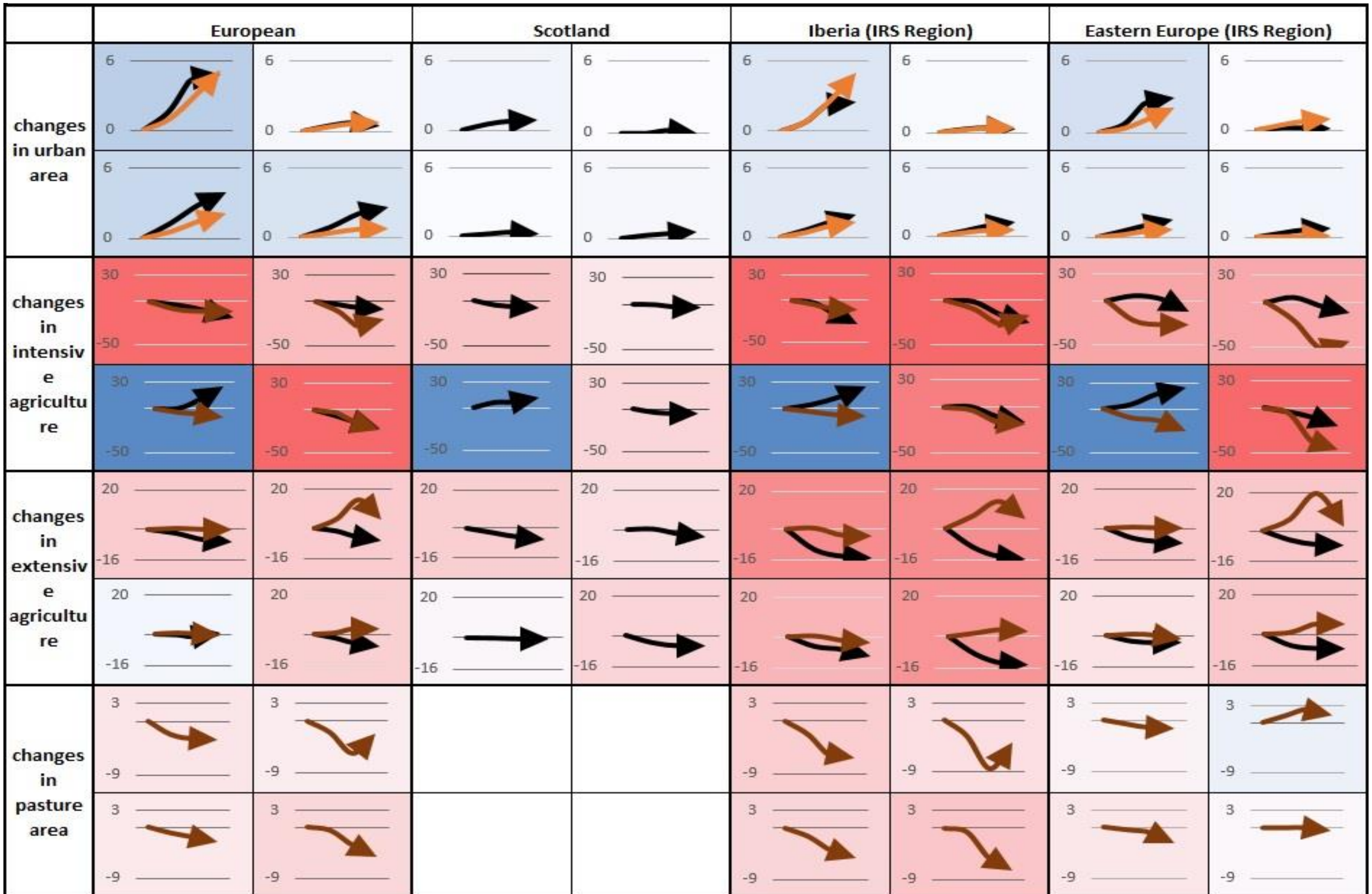
Figure 26: Matrices exemplifying the arrangement of scenarios in the synthesis tables, with four integrated climate (RCP) and socio-economic (SSP) scenarios (on the left) and two climate-only (RCP) scenarios (right). Note all impacts are based on the HadGEM2-ES global climate model downscaled with the RCA4 regional climate model for both RCPs.

5.2. Land use (agriculture/urban)

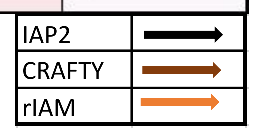
Land use changes across Europe show some interesting, and potentially linked, patterns (Table 1). Urban areas increase under all scenarios and across all case studies, but are highest under SSP5, due to urban sprawl. The increases are very moderate in Scotland, showing comparatively little change. This is related to a difference in geographical context, as Scotland is characterised by large areas with highly dispersed populations. The increases across the whole of Europe are slightly higher than in each of the case study regions, because the most densely populated areas are outside the IMPRESSIONS case study regions (areas such as southern UK, Germany, France and the Benelux countries; see Kotzeva et al. [2016]). Data from the rIAM (orange) shows smaller increases under SSP1, SSP3 and SSP4. Increases are, however, slightly higher for SSP5. This is a reflection of the model differences outlined in Section 3.5. Inputs from the socio-economic scenarios play a more important role in rIAM than in IAP2, explaining the higher increase in urban areas under SSP5, both in relation to the other scenarios, but also the difference between the two models. The SSP5 narrative involves a much higher population growth than in any other scenario as well as little urban planning regulations, thereby also leading to greater growth in urban areas in a sprawled manner. The relatively small increases in urban areas under SSP3 are because this scenarios narrative has a decreasing population.

The outcomes and directions of change for agricultural area show a more diverse pattern of change (Table 1). The most extreme changes (both increases and decreases) are found for intensive agriculture (dark red and blue background colours). Substantial increases in intensive agriculture are seen across all case studies under SSP1. This is explained by the scenario narrative, as locally or nationally grown food (see especially the Scottish case study) becomes more important (as food imports are decreased), combined with a focus on sustainable agriculture. However, under the other scenarios, intensive agricultural area decreases. The decreases are highest under SSP5 due to the high-tech nature of agriculture in this scenario meaning that less area is needed to produce food. This is particularly pronounced in Iberia with a decrease of almost 29%. The sub-region of Eastern Europe (representing the Hungarian case study) shows slightly different trends: initial small increases under SSP4 and SSP5 are followed by decreases later in the century. Changes in Scotland are much more moderate compared to the other cases and regions. The outcomes for extensive agriculture are more consistent across all cases and scenarios showing predominantly projected decreases. The decreases are greatest in Iberia and most moderate in Scotland.

Table 1: Synthesis table showing the direction and broad magnitude of impacts for land use indicators. All indicators show percentage changes relative to baseline. Background colours reflect the magnitude of changes in percentiles and refer to changes in IAP2 indicators rather than CRAFTY or rIAM. Ranges on the y-axis show the broad range of values across one indicator. Integrated scenarios are displayed in four quadrants per indicator and case study: clockwise from the top left = RCP8.5 x SSP5; RCP8.5 x SSP3; RCP4.5 x SSP4; RCP4.5 x SSP1.



Percentile	5	25	45	Midpoint set to 0	55	75	95



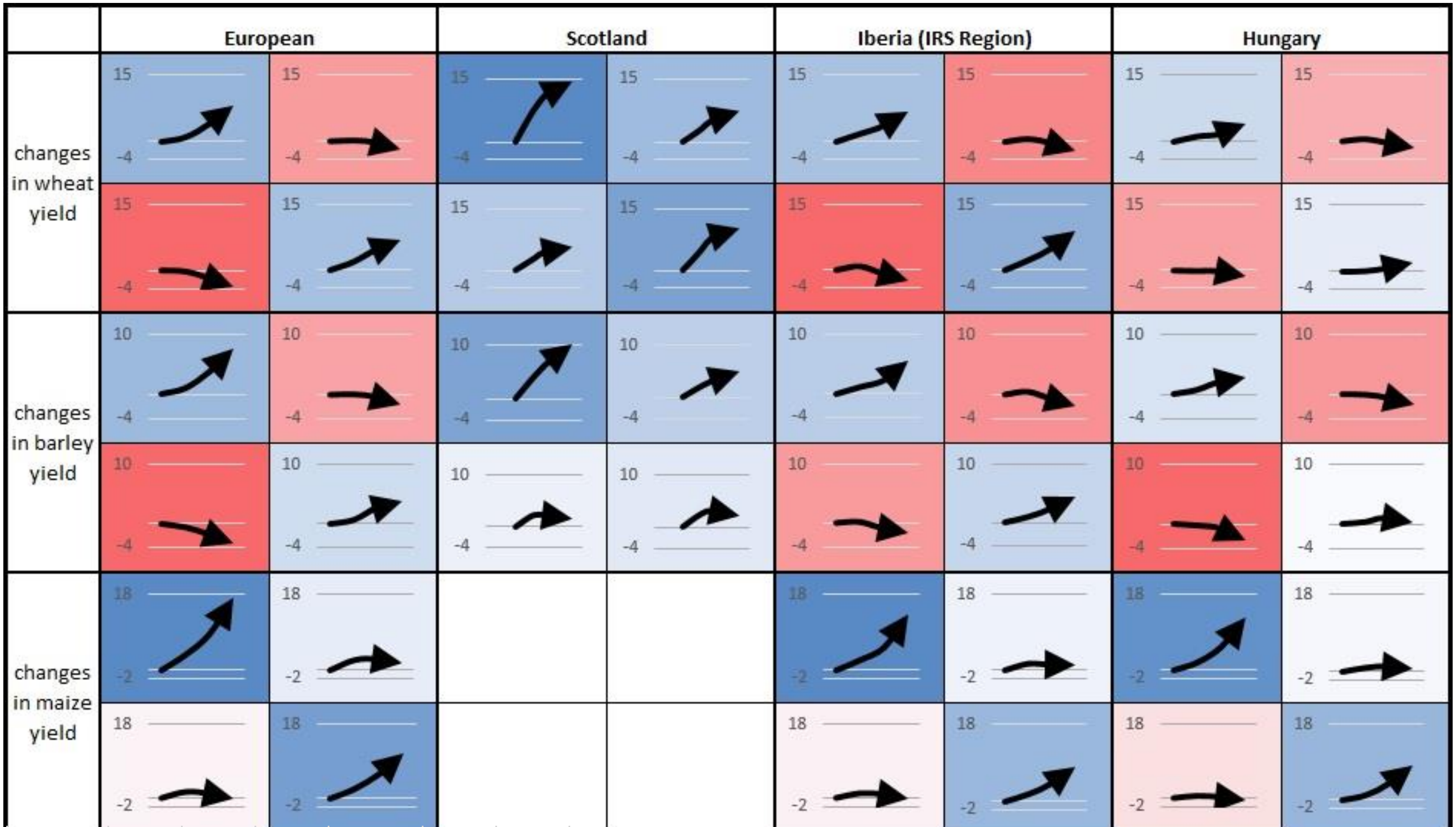
CRAFTY (brown arrows) shows different trends, with decreases under SSP1 for intensive agriculture and much greater decreases than the IAP2 under SSP3. For extensive agriculture, CRAFTY projects increases under SSP3 and SSP4, in contrast to the decreasing trend projected by IAP2. These increases are strong in Iberia and Eastern Europe. Under SSP3, the increases in extensive agriculture are, however, not consistent across time slices. The initial increases are followed by decreases during the last time slice. This decrease is greatest in Hungary, where between 2040 and 2070, extensive agriculture increases by 20% and then drops to only 2% relative to the baseline. The reasons for the modelling differences are outlined in Section 3.4.

5.3. Crop yields

Crop yield outcomes are relatively consistent across cases and scenarios for Europe, Hungary and Iberia, with decreases or minor increases observed under SSP1 and SSP3 (Table 2). The largest increases are found under SSP5 and SSP4. These increases are in line with assumptions made particularly under SSP5, as investments are made into technology to increase agricultural outputs. Hungary shows a modest increase for wheat and barley in comparison to increases in Europe, Iberia and Scotland. Only Scotland shows consistent increases in yields across all scenarios, indicating that increased temperature might be beneficial to agricultural outputs in Scotland. Maize was not included in the synthesis table for Scotland, due to its limited relevance in the country. It has to be noted, however, that two of the climate models in the Scottish IAP2 start to grow maize in certain grid-cells by the end of the century under SSP5 (excluding forage maize). This indicates that with higher temperatures, maize might become a viable crop in Scotland. Maize yields show the most consistent increases across cases. Yields remain relatively stable under SSP1 and SSP3 while they increase strongly under SSP4 and SSP5. European maize yields under SSP5 also show the highest overall increases across all crops and cases.

The varying outcomes according to scenarios can be partly explained by the scenario narratives. Under SSP1 there is a greater focus on sustainable agriculture resulting in lower artificial inputs, which leads to a decrease in yields. Under SSP5, technological developments, particularly fossil-fuel based technologies, lead to increases in crop yields. While the increases under SSP4 can be explained by improvements in green technologies leading to agricultural innovation.

Table 2: Synthesis table showing the direction and broad magnitude of impacts for crop yields (IAP2). Unit is t/ha relative to baseline. Background colours reflect the magnitude of changes in percentiles. Ranges on the y-axis show the broad range of values across one indicator. Integrated scenarios are displayed in four quadrants per indicator and case study: clockwise from the top left = RCP8.5 x SSP5; RCP8.5 x SSP3; RCP4.5 x SSP4; RCP4.5 x SSP1.



Percentile	5	25	45	Midpoint set to 0	55	75	95

5.4. Forestry

Managed forest area decreases all over Europe in the IAP2 (Table 3). Conversely, European results from the CRAFTY model shows managed forest area to remain relatively stable, with only minor increases and decreases. The exception is Eastern Europe under SSP3, where managed forest area increases by 17.7%. This reflects a preference of the models (see section 3.4); CRAFTY assigns more forest area, while IAP2 projects more agricultural area to satisfy food demand from an increasing population.

Unmanaged forest area shows an increase under almost all scenarios; only under SSP1 unmanaged forest areas decrease slightly or remain relatively stable (Table 3). This is because SSP1 has more agricultural land in order to meet food demand with lower imports and more sustainable agricultural practices, which comes at the expense of unmanaged forests. Under the remaining scenarios, agricultural area decreases, potentially resulting in re-naturalisation in the form of unmanaged forest areas. Unmanaged forest areas in Iberia under SSP3, SSP4 and SSP5 fluctuate significantly: increases are followed by decreases. This is particularly evident under SSP4, where unmanaged forest area increases to almost 20%, then decreases to 9% followed by an increase to 31% in the last time slice (values reflect absolute changes relative to baseline). CRAFTY modelling results for unmanaged forest area shows much smaller changes compared to the IAP2 results. The highest increase for the last time slice is 6% in Eastern Europe.

For forest productivity, changes are summarised for Iberia only as other forest productivity model outputs were not compatible with the format of the synthesis tables and so, it was not possible to compare outputs. Iberia provides an interesting example of significant changes in the forestry sector (Table 4). Oak and cork production analysed in Iberia is projected to decrease, significantly impacting traditional lifestyles and traditions of agroforestry. For a detailed exploration of the issues see Deliverable D3C.2 (Clarke et al., 2017). However, as highlighted in Section 3.2, forest productivity is expected to increase in northern Europe and mountain areas, while it is expected to decrease in southern Europe. The impacts in Scotland are slightly more mixed (not shown in synthesis table), with productivity for Douglas fir and Sitka spruce projected to increase, while the native Scots pine does not fare as well under high-end climate change. These results highlight the need to identify tree species that will be well suited to future climate change to ensure viability and resilience of forestry sectors in different parts of Europe.

Table 3: Synthesis table showing the direction and broad magnitude of impacts for forest indicators from the IAP2 and CRAFTY models. Arrows show percentage change relative to baseline. Background colours reflect the magnitude of changes in percentiles. Ranges on the y-axis show the broad range of values across one indicator. Integrated scenarios are displayed in four quadrants per indicator and case study: clockwise from the top left = RCP8.5 x SSP5; RCP8. 5x SSP3; RCP4.5 x SSP4; RCP4.5 x SSP1.

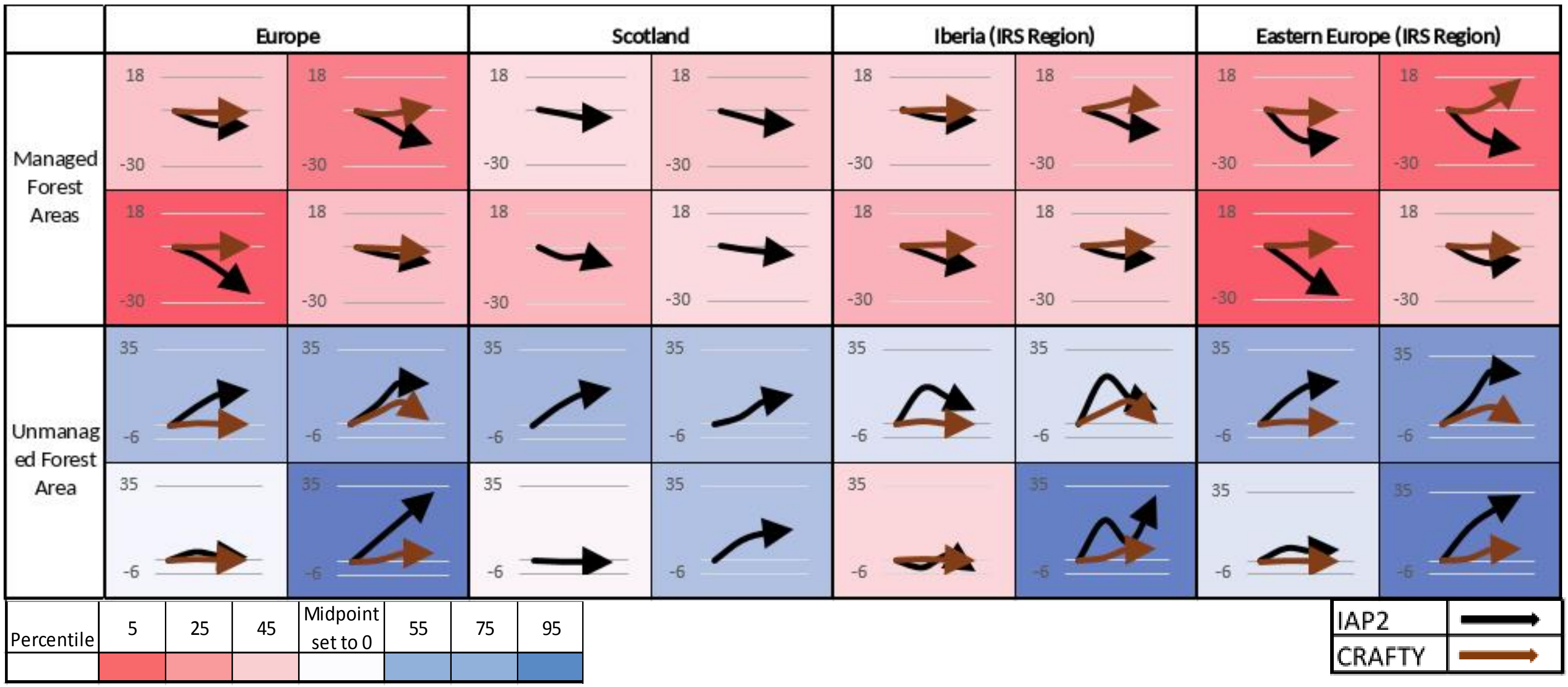
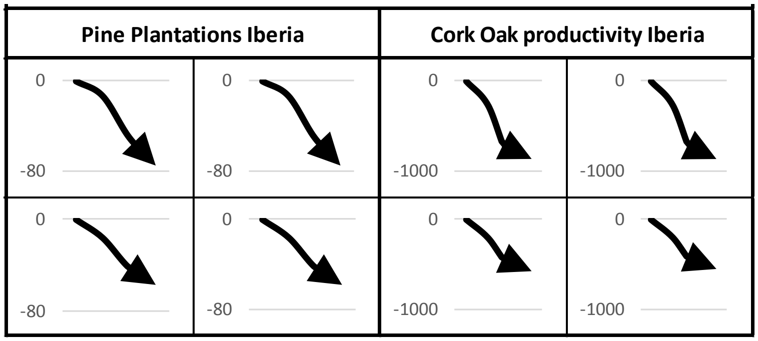


Table 4: Synthesis table showing the direction of impacts for tree species productivity in Iberia based on the LandClim model. Units of Indicators: Pine plantations = m3/ha; Cork oak = kg/ha. No background colours are shown as the indicators are for the same case study and the direction of change is similar in magnitude. Ranges on the y-axis show the broad range of values across one indicator. Integrated scenarios are displayed in four quadrants per indicator and case study: clockwise from the top left = RCP8.5 x SSP5; RCP8.5 x SSP3; RCP4.5 x SSP4; RCP4.5 x SSP1.



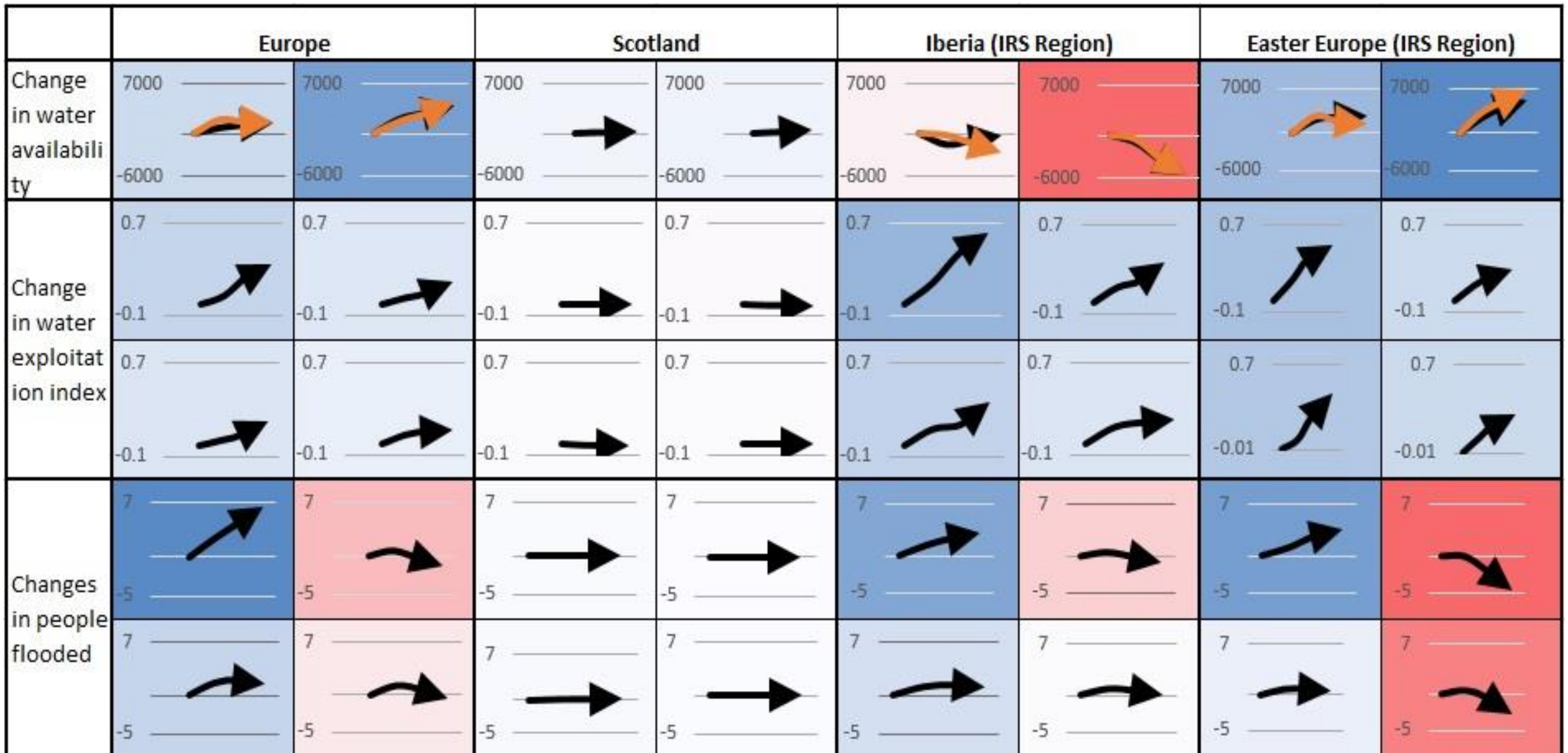
5.5. Water

On average, water availability is projected to increase across Europe (Table 5). However, Iberia is likely to suffer from a decrease in water availability under high-end climate change due to decreases in precipitation and higher evapotranspiration, while in Scotland, water availability remains relatively constant due to increases in precipitation.

The water exploitation index (WEI), which shows water demand as a proportion of availability, increases in Europe and across the regional/local case studies, showing that a higher proportion of available water is being used (Table 5). The index only remains stable for Scotland, showing very small decreases, indicating that Scotland is not going to be vulnerable to overexploitation of water. This is a reflection of the abundance of water resources available in Scotland, increases in precipitation in the climate scenarios and the relatively low population density even under future scenarios. Increases in the index are particularly high in Iberia, which is related to projected decreases in precipitation coupled with greater evapotranspiration due to higher temperatures and greater water demands for agricultural and other purposes. Without appropriate action, Iberia as well as Eastern Europe will suffer severe water stress under SSP5. A WEI of ≥ 0.4 generally indicates severe water stress, where regions are vulnerable to water exploitation. A WEI of 1 or greater is generally seen as the point after which societies will be unable to cope with water stress. An in-depth exploration of regional variations in WEI across Europe is given in Deliverable D3B.2 (Holman et al., 2017).

The likelihood of people being flooded rises under SSP1 and SSP5 in Europe as well as Iberia and Eastern Europe (Table 5). In Scotland, on the other hand, flood risk remains stable, with the number of people expected to be flooded only increasing marginally. This lack of vulnerability to flooding in the Scottish case study is an important element in both the scenarios as well as the pathways. The model simulations show the highest increases are projected under the SSP5 scenario in Europe, Iberia and Eastern Europe. Decreases are projected under the SSP3 and SSP4 scenarios; these are particularly strong in Eastern Europe and strongest for the SSP3 scenario. The strong decreases under SSP3 are related to a declining population in most areas of Europe. Under the SSP5 scenario, population increase combined with higher flood risk under high-end climate change leads to more people being flooded. For further details, see Deliverable D3B.2 (Holman et al., 2017).

Table 5: Synthesis table showing the direction and broad magnitude of impacts for water indicators. Units of Indicators: water availability = mill. m³/a; changes in people flooded = x100 persons. Background colours reflect the magnitude of change in percentiles. Ranges on the y-axis show the broad range of values across one indicator. Integrated scenarios are displayed in four quadrants per indicator and case study: clockwise from the top left = RCP8.5 x SSP5; RCP8.5 x SSP3; RCP4.5 x SSP4; RCP4.5 x SSP1.



Percentile	5	25	45	Midpoint set to 0	55	75	95

IAP2	→ (black)
rIAM	→ (orange)

Changes in river discharge are modelled using the SWIM model (see Section 3.3) using inputs from RCPs without socio-economic inputs from SSPs. Consequently, there are only two scenarios rather than four for each time slice. Looking at the selected river catchment areas reveals a diverse picture of impacts (Table 6). While discharge is expected to increase in the rivers Rhine and Tay for both RCP4.5 and RCP8.5, the discharge of the river Tagus will decrease significantly, almost 50% by 2100 under RCP8.5, relative to the baseline. According to the projected results, the Danube will experience a 10% decrease in discharge by the end of the century under RCP4.5. The modelling results for the Danube under RCP8.5 show a slight decrease over the first two time slices followed by an increase at the end of the century. Peak inflows into the Tomkogul reservoir of the Syr Darya catchment area, studied as part of the Central Asia (EUx) case study, are likely to increase.

High flow events are likely to increase in the rivers Rhine and Tay, especially under the RCP8.5 scenario. High flow events for the case of the river Tagus are projected to decrease slightly under RCP4.5 and significantly under RCP8.5. The Danube is expected to experience fewer high flow events under RCP4.5, while the number of high flow days is expected to increase under RCP8.5. The rivers Syr Darya and Amu Darya (of the Central Asia (EUx) case study area) show a slight increase in peak flows under RCP4.5 and a slight decrease under RCP8.5. For further details on all the water indicators, see Deliverables D3B.2 (Holman et al., 2017) and D3C.2 (Clarke et al., 2017).

Table 6: Synthesis table showing direction and broad magnitude of changes in select river catchments: data from the SWIM model. For changes in discharge the Central Asia data reflects peak inflows into the Tomkogul reservoir in the Syr Darya Catchment. For changes in flooding the Central Asia data shows the peak flows of Amu Darya and Syr Darya, as the changes are similar. The Central Asia data only shows change from baseline to 2100. All arrows show percentage change relative to baseline. Background colours reflect the magnitude of changes in precentiles. Ranges on the y-axis show the broad range of values across one indicator. Scenarios are displayed per indicator: RCP4.5 on the left, RCP8.5 on the right.

River System	Rhine		Tay		Tagus	
Changes in discharge	18 / -50	18 / -50	18 / -50	18 / -50	18 / -50	18 / -50
Changes in flooding	300 / -100	300 / -100	300 / -100	300 / -100	300 / -100	300 / -100

River System	Danube		Amu Darya and Syr Darya	
Changes in discharge	18 / -50	18 / -50	18 / -50	18 / -50
Changes in flooding	300 / -100	300 / -100	5 / 0 / -5	5 / 0 / -5

Percentile	5	25	45	Midpoint set to 0	55	75	95

5.6. Social and wellbeing

As highlighted in the scenario narratives, each scenario assumes a different population development. For Europe, under SSP1 there is limited population growth; under SSP5 there is strong population growth; under SSP3 population is projected to continually decrease; while under SSP4 after initial increases, the population decreases toward the end of the century. In the Hungarian case study, population is expected to decrease under all scenarios except SSP5. In the Scottish case study, population is expected to increase under all scenarios, with the exception of SSP3, where population decreases. The highest population growth is expected under SSP1.

The ecosystem services supply/demand gap has been modelled under CRAFTY. This indicator shows the proportional gap in the supply and demand of different ecosystem services. The indicator has been included among the wellbeing indicators as it analyses the continued provision of key ecosystem services crucial to human wellbeing. The supply of ecosystem services across Europe is projected to meet the demand of scenarios SSP1, SSP4 and SSP5 (Table 7). However, under SSP3 a shortfall is projected. This is in line with the European scenario storyline for SSP3, which imagines a Europe that relies on significant resource inputs to keep the economy growing. This leads to environmental degradation and a decline in ecosystem service provision.

The potential spread of Lyme disease under high-end climate change was analysed for the Scottish and Hungarian case studies (Table 7). This found that the number of infectious ticks per km^2 will likely increase in both cases, as rising temperatures have a positive impact on tick populations as well as extending the period when ticks are actively questing for new hosts. This causes more frequent tick-host contacts to take place over an extended period of time, thereby increasing the likelihood of Lyme disease spreading to the human population. The increases are particularly strong in Scotland (see Deliverable D3C.2 [Clarke et al., 2017]). The increased risk of Lyme disease in these areas necessitates that health practitioners and people at risk are aware of what to do in the case of tick bites, as well as how to recognise the symptoms of Lyme disease.

Heat mortality was calculated across Europe for three different age groups (0-64, 65-74 and ≥75), as well as considering the impacts of adaptation measures on mortality rates (Table 8). As highlighted in Deliverable D3B.2 (Holman et al., 2017), adaptation measures only appear to have a moderate effect on the number of heat related deaths (see Table 9 for impacts with no adaptation measures). Adaptation measures include improvements in housing design and urban planning, and heat wave plans with a particular focus on older and vulnerable citizens. Not surprisingly, the most severely impacted age group across Europe are people over the age of 75. For this age group, increases are highest for scenarios SSP5 and SSP3, which are associated with the high-end climate scenario of RCP8.5. The highest increases take place in Iberia, while in Scotland heat related mortality remains relatively stable. This is in line with the lower temperature increases projected to take place in Scotland relative to the rest of Europe. The development of heat mortality rates is dependent on population development and particularly on population ageing. A detailed exploration of this topic can be found in Deliverable D3B.2 (Holman et al., 2017).

Table 7: Synthesis table showing the direction and broad magnitude of impacts for human wellbeing indicators. Lyme disease risk, based on the LYR model, shows the change in the number of infectious questing nymphal ticks per km^2. The ecosystem services supply shows the proportional gap across different services; Values are normalized so that numbers >1 show overproduction and numbers <1 reflect shortfall. Background colours reflect the magnitude of changes in precentiles. Ranges on the y-axis show the broad range of values across one indicator. Integrated scenarios are displayed in four quadrants per indicator and case study: clockwise from the top left = RCP8.5 x SSP5; RCP8.5 x SSP3; RCP4.5 x SSP4; RCP4.5 x SSP1.

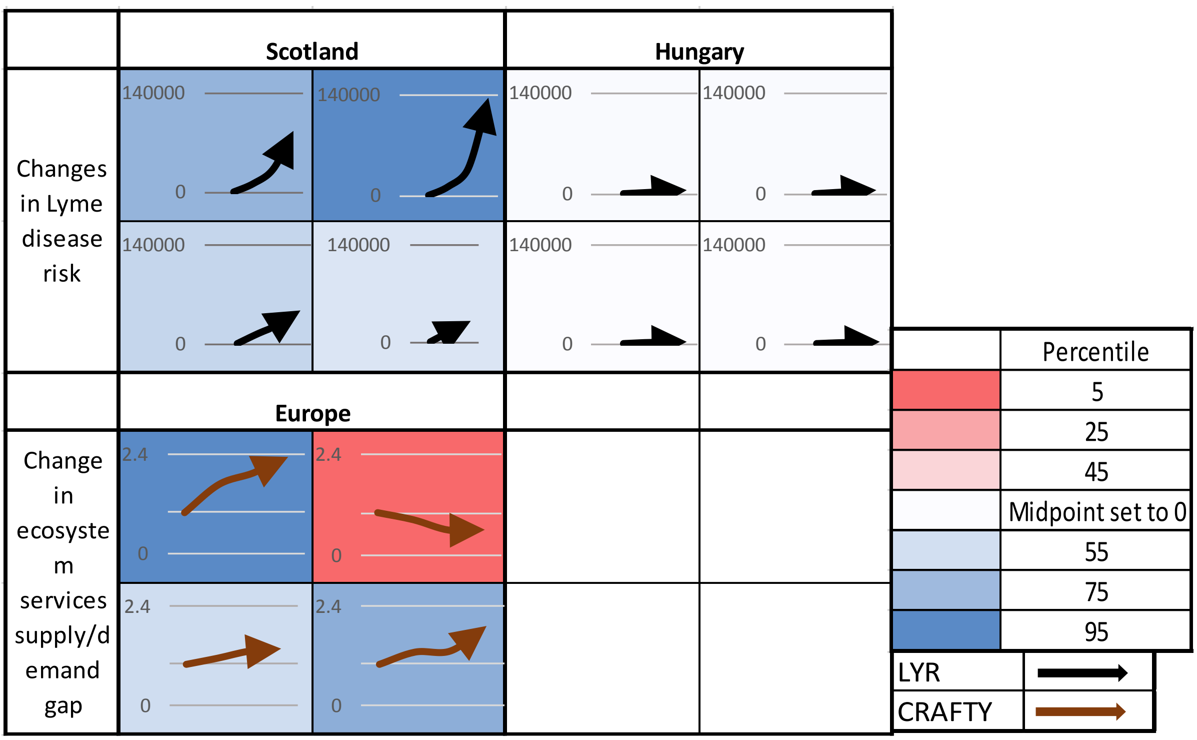
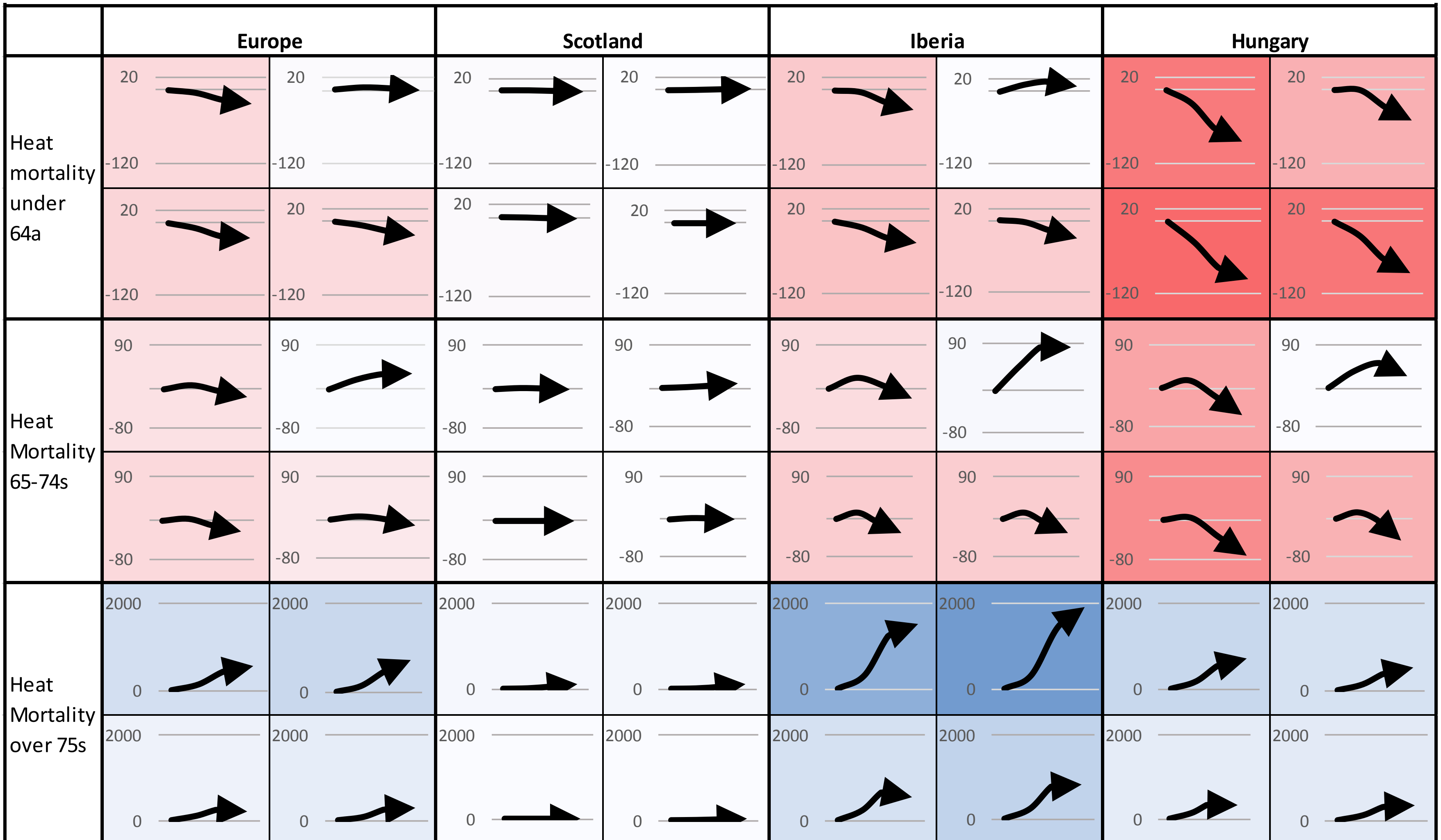
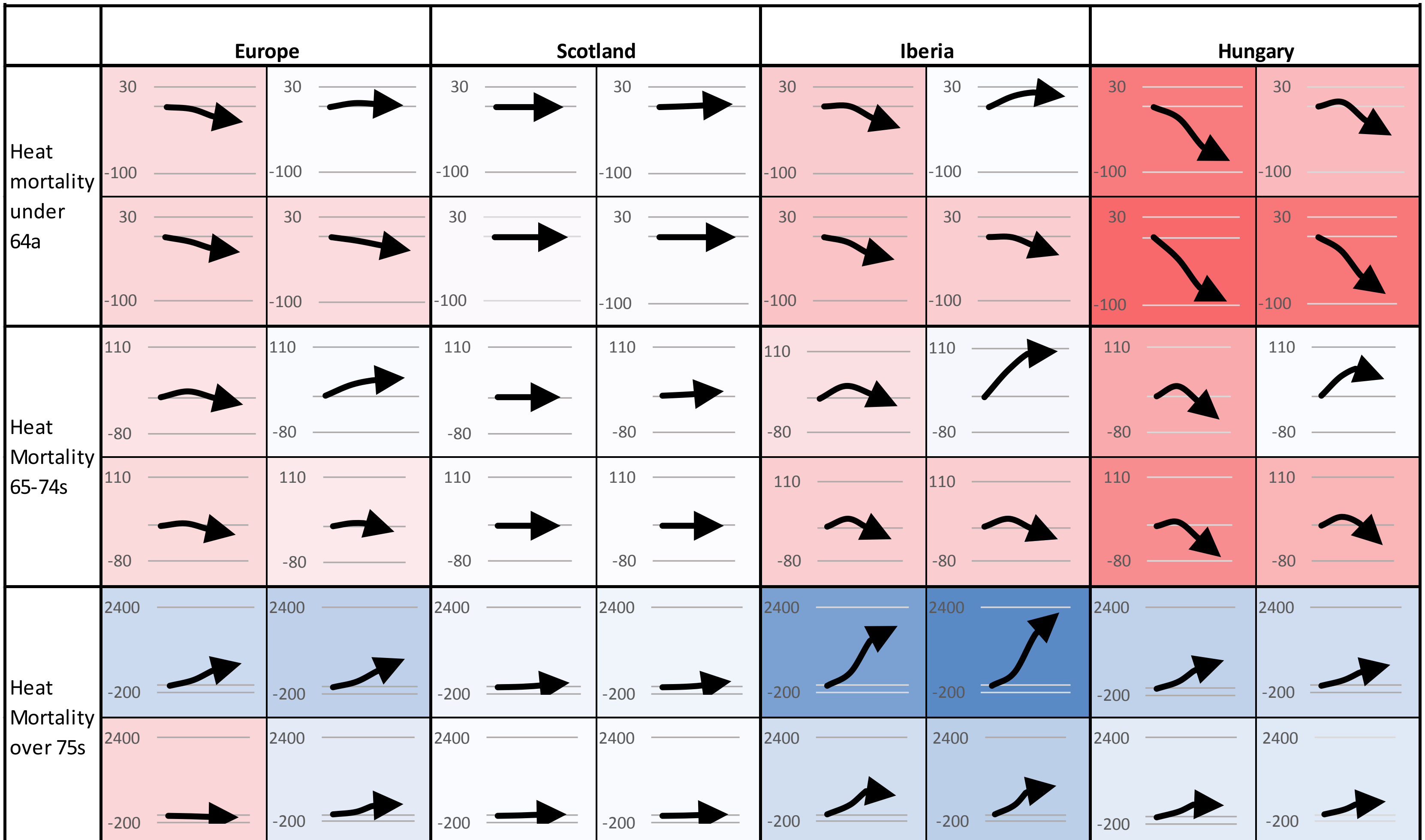


Table 8: Synthesis table showing the direction and broad magnitude of impacts of the integrated scenarios on heat mortality with adaptation measures. Data from the HEET model. Note that regions correspond to European NUTS2 regions. Background colours reflect the magnitude of changes in precentiles. Ranges on the y-axis show the broad range of values across one indicator. Integrated scenarios are displayed in four quadrants per indicator and case study: clockwise from the top left = RCP8.5 x SSP5; RCP8.5 x SSP3; RCP4.5 x SSP4; RCP4.5 x SSP1.



Percentile	5	25	45	Midpoint set to 0	55	75	95

Table 9: Synthesis table showing the direction and broad magnitude of impacts for heat mortality with no adaptation measures. Data from the HEET model. Note that regions correspond to European NUTS2 regions. Background colours reflect the magnitude of changes in percentiles. Ranges on the y-axis show the broad range of values across one indicator. Integrated scenarios are displayed in four quadrants per indicator and case study: clockwise from the top left = RCP8.5 x SSP5; RCP8.5 x SSP3; RCP4.5 x SSP4; RCP4.5xSSP1.



Percentile	5	25	45	Midpoint set to 0	55	75	95

6. The Central Asia (EU external) case study

6.1. Background

The EU External (EUx) case study differs from the other IMPRESSIONS case studies in Europe in two main ways:

1. While the other case studies have investigated the direct impacts of climate change on the case study regions themselves, the objective of the EUx case study was to rethink EU strategies towards Central Asia in light of high-end socio-economic and climate change scenarios, taking into consideration geopolitical dynamics with Russia and China. Hence, the interest was to understand the implications of direct climate change impacts in one region – Central Asia[2] – for the EU, to whom these can be regarded as indirect or "cross-border" impacts (see Deliverable D3A.2 [Benzie et al., 2017]).
2. As no CCIAV models existed for Central Asia within the IMPRESSIONS consortium, EUx has relied on climate change impact assessments for Central Asia from the literature in addition to new global modelling work that was carried out in IMPRESSIONS. This was achieved by mapping results from the literature to the four scenarios developed in this case study.

The Central Asia region is not well covered in many global climate and integrated assessment models. For example, it is frequently grouped together with other countries into a "former-Soviet Union" region, despite the very different socio-economic, topographical and climatic contexts of countries within this grouping. Furthermore, it has not been studied much at the regional scale in previous climate impacts, vulnerability and adaptation research. While various studies exist with a more local focus within Central Asia, because the case study looked at the region as a whole (including transboundary natural and human systems), the literature base upon which to draw for this regional case study was thinner than that which is available for other world regions.

The four SSP x RCP scenarios specifically developed for the EUx case study were:

- Utopistan (SSP1 x RCP4.5 moderate climate change)
- Regional Rivalry (SSP3 x RCP8.5 high-end climate change)
- A Game of Elites (SSP4 x RCP4.5 moderate climate change)
- Fossil-Fuelled Development (SSP5 x RCP8.5 high-end climate change)

The following two sections first summarise the direct impact of climate change in Central Asia. These were presented in the second of a series of three stakeholder workshops. Some of the impacts that have been modelled as part of the IMPRESSIONS project including elements of the stakeholder-developed scenarios as direct inputs to new impact modelling carried out in the case study. The second section attempts to relate qualitatively the impacts in Central Asia to the EU, based on discussions held at the stakeholder workshops.

6.2. Direct impacts of climate change in Central Asia

A synthesis of direct impacts of climate change in Central Asia is given in Tables 10 and 11 and Figures 27 a-d. Climate change impacts with substantial differences across the scenario-combinations are given in Table 10, whereas impacts common across all scenarios are given in Table 11. Interactions

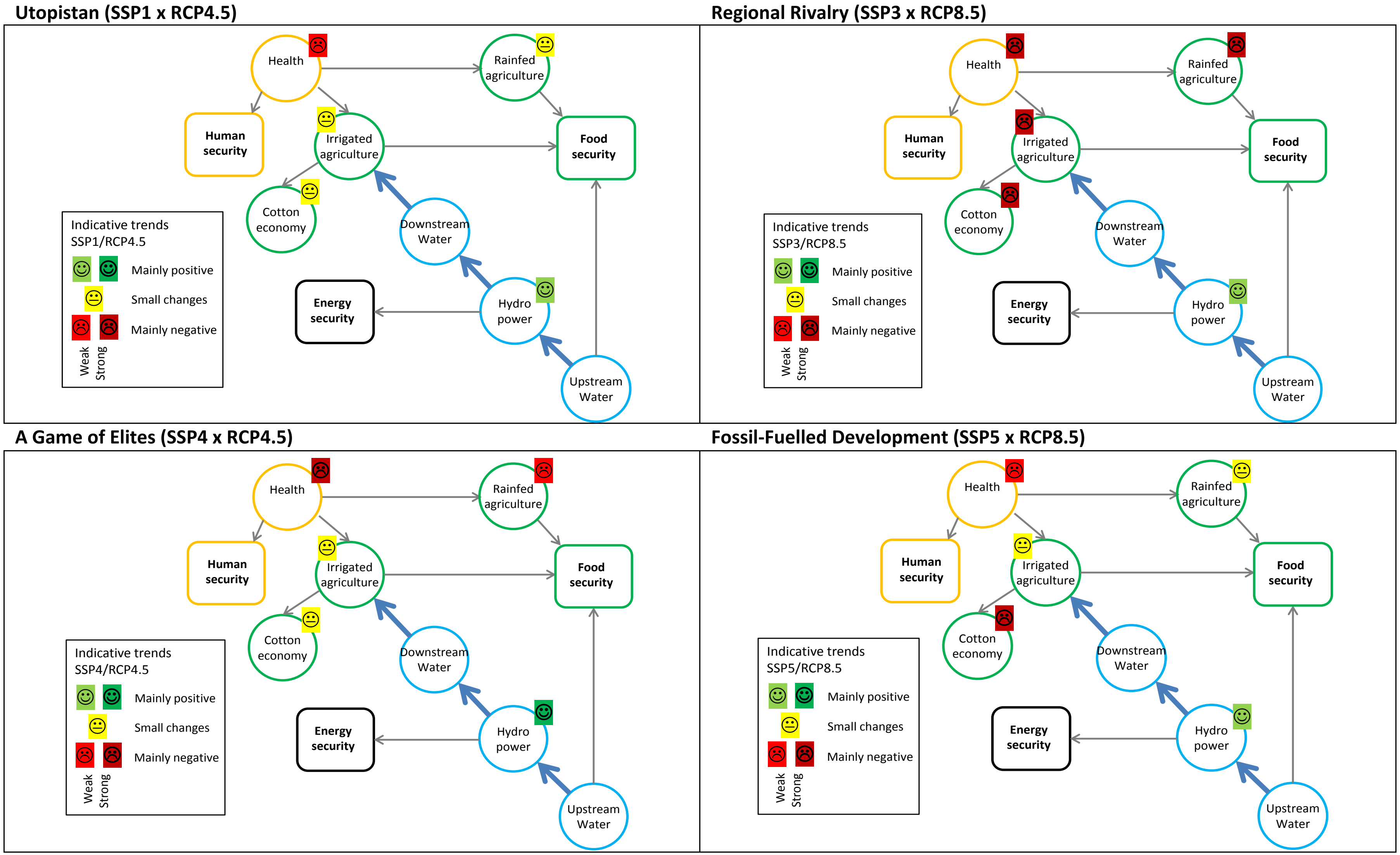
[2] The Central Asian case study region consists of the five former Soviet republics Kazakhstan, Uzbekistan, Turkmenistan, Kyrgyzstan and Tajikistan.

between the impacts under each integrated scenario is illustrated as a network diagram with icons indicating positive, negative or stable changes in impacts in Figures 27 a-d. Details of direct impacts of climate change in Central Asia for water-related variables were presented in Deliverable D3A.1 (Carter et al., 2016, Section 4.2).

Table 10: Climate change impacts for the Central Asia case study with substantial differences across the scenario-combinations.

Indicator	Utopistan SSP1 x RCP4.5	Regional Rivalry SSP3 x RCP8.5	A Game of Elites SSP4 x RCP4.5	Fossil-Fuelled Development SSP5 x RCP8.5
Greenhouse gas emissions*	Peak in 2040, then decline due to increased mitigation efforts.	Increase throughout the 21st century to a high level.	Peak in 2040, then decline due to increased mitigation efforts.	Increase throughout the 21st century to a high level.
Warming and precipitation*	Moderate warming and increases in precipitation (strongest in the north-east), but also increases in extreme heat, rainfall and drought events.	Strong warming and increases in precipitation (strongest in the north-east), but also increases in extreme heat, rainfall and drought events.	Moderate warming and increases in precipitation (strongest in the north-east), but also increases in extreme heat, rainfall and drought events.	Strong warming and increases in precipitation (strongest in the north-east), but also increases in extreme heat, rainfall and drought events.
Household water use and irrigation**	Likely to decline.	Likely to decline.	Will increase.	Remains stable until 2050 and then increases slightly, whereas irrigation water demand declines (especially from the 2050s).
Cotton and wheat production**	Could be increased, but this is highly dependent on the availability of irrigation water.	Remain far below their potential, because water for irrigation is not made available at the times when needed.	Could slightly increase as agreements on the use of water resources allow continuing some irrigation.	Becomes less important and is finally replaced by export crops that are less dependent on irrigation, wheat production increases.

* Specific to the (RCP-based) climate projection of that scenario
** Specific to the (SSP-based) socio-economic storyline in addition to the climate projection



Figures 27 a-d: Relationships between key elements of the Central Asia case study and indicative trends under four integrated scenarios.

Table 11: Climate change impacts for the Central Asia case study with similarities across the scenario-combinations.

Indicator	Across all scenario-combinations
Heat-related mortality**	Increased risks of heat-related human mortality and adverse effects on labour productivity.
Snow season*	Shortens, and glaciers continue to shrink.
Precipitation*	The region gets wetter in the north and drier in the south (north-east to south-west division).
Water flows*	The seasonality of water resources shifts with generally reduced summer water flows and increased year-to-year variability.

* Influenced by (RCP-based) climate projection only
** Influenced by the (SSP-based) socio-economic storyline in addition to the climate projection

6.3. Indirect impacts for the European Union

The implications of the climate change impacts in Central Asia for the EU were qualitatively explored for energy security, trade, conflict and security, and migration, taking the political and socio-economic scenario circumstances into consideration.

6.3.1. Energy

EU access to Central Asian oil and gas resources was expected to decrease under the Utopistan (SSP1 x RCP4.5) scenario and increase in A Game of Elites (SSP4 x RCP4.5) and Fossil-Fuelled Development (SSP5 x RCP8.5) (Table 12). This is largely an effect of differences in energy pathways between the scenarios, where a focus on renewable energy sources is assumed in Utopistan, whereas SSP5 represents a fossil-fuel dependent world. Consequently, interdependence between the EU and Central Asia on renewable energy increases in SSP1. These trends are also affected by direct climate change impacts, for example, the positive trends in hydropower (see Figure 27) and possible increasing risks to energy infrastructure due to increases in extreme precipitation events and high river flows in the northern parts of Central Asia (which are larger under RCP8.5 than RCP4.5).

Table 12: Qualitative interpretations of cross-border effects from impacts in Central Asia to the EU for the energy sector for the four integrated scenarios in the EUx case study. Red colour indicates a decrease, and blue colour indicates an increase, with the deeper shades of colour and thicker trend lines showing a higher magnitude of change. The end of the century time slice determines the colour. The arrows are approximations of the direction of change over time.

Indicators	Utopistan (SSP1 x RCP4.5)	Regional Rivalry (SSP3 x RCP8.5)	A Game of Elites (SSP4 x RCP4.5)	Fossil-Fuelled Development (SSP5 x RCP8.5)
EU access to Central Asian oil and gas				
EU-Central Asia renewable energy interdependence				

6.3.2. Trade

Trade opportunities represent a significant share of the EU's interest in Central Asia, despite current low volumes and value of direct trade between the two regions. The value of EU-Central Asia trade is expected to increase under Utopistan, A Game of Elites and especially the Fossil-Fuelled Development scenario (Table 13). Agricultural exports from Central Asia to Europe are likely to rise in Utopistan, including diversified products such as fibres, fruit, vegetables and bioenergy crops. The increased efficiency of Central Asian agriculture in the Fossil-Fuelled Development scenario is also likely to increase agricultural exports to the EU. A similar pattern is expected for non-agricultural exports, with export categories collapsing under Regional Rivalry and low for the A Game of Elites scenarios.

Trade across the broader Eurasian region – for example between China, Central Asia, Russia, Southern Asia and the EU – was considered to be closely related to the building of pan-Eurasian infrastructure, as envisaged by China's Belt and Road Initiative. Both Utopistan and Fossil-Fuelled Development are conducive to major infrastructure connectivity, and therefore are expected to see big increased in pan-Eurasian trade, which opens up a number of land trade opportunities for the EU. The partial completion of Belt and Road Initiatives in A Game of Elites and their collapse under Regional Rivalry mean prospects are much lower in these scenarios. The risk of an increase in climate-related hazards on infrastructure, e.g. through extreme precipitation and floods, is larger under RCP8.5 than RCP4.5.

Table 13: Qualitative interpretations of cross-border effects from impacts in Central Asia to the EU for trade for the four integrated scenarios in the EUx case study. Red colour indicates a decrease, and blue colour indicates an increase, with the deeper shades of colour and thicker trend lines showing a higher magnitude of change. The end of the century time slice determines the colour. The arrows are approximations of the direction of change over time.

Indicators	Utopistan (SSP1 x RCP4.5)	Regional Rivalry (SSP3 x RCP8.5)	A Game of Elites (SSP4 x RCP4.5)	Fossil-Fuelled Development (SSP5 x RCP8.5)
Value of EU-Central Asia trade overall				
Agricultural exports from Central Asia to EU				
Non-agricultural exports from Central Asia to EU				
Pan-Eurasian trade				

6.3.3. Conflict and security

The EU will be indirectly affected by any worsening of the security situation in Central Asia, for example by disruption to energy or commercial trade, by potential changes to migration into Europe, or by geopolitical instability that may involve or otherwise threaten the EU's interests globally. EU involvement with peacekeeping in Central Asia is expected to increase under the Regional Rivalry scenario, in particular (Table 14). Direct engagement by the EU in Central Asian security is unlikely, but possibly foreseen under the Regional Rivalry and A Game of Elites scenarios, where EU forces may be used to prop up elite regimes. Security threats from Central Asia to Europe might increase under these two scenarios, for example if instability under Regional Rivalry leads to the radicalisation and militarisation of marginalised groups within Central Asian republics.

Table 14: Qualitative interpretations of cross-border effects from impacts in Central Asia to the EU for conflict and security for the four SSP-based scenarios in the EUx case study. Red colour indicates a decrease, and blue colour indicates an increase, with the deeper shades of colour and thicker trend lines showing a higher magnitude of change. The end of the century time slice determines the colour. The arrows are approximations of the direction of change over time.

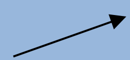
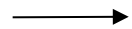
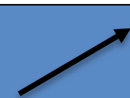
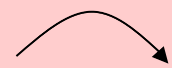
Indicators	Utopistan (SSP1 x RCP4.5)	Regional Rivalry (SSP3 x RCP8.5)	A Game of Elites (SSP4 x RCP4.5)	Fossil-Fuelled Development (SSP5 x RCP8.5)
EU involvement in peacekeeping in Central Asia	→	↗↘	↗	↘
Direct engagement by EU in Central Asia security	↘	→	→	↘
Security threats from Central Asia to EU	↘	↗	↗	↘

6.3.4. Migration

Current migration flows between Central Asia and the EU are small, but might increase in the future, depending on developments in both regions. Skilled migration and facilitated exchange may increase significantly under the A Game of Elites scenario, and to a lesser extent in others: population growth and improved education under Utopistan may boost this, though overall out-migration from Central Asia is projected to be low.

Forced migration was expected to increase – via illicit networks in Regional Rivalry, especially following large scale conflict mid-century – and also under A Game of Elites – but is likely to decrease or be negligible under Utopistan and Fossil-Fuelled Development.

Table 15: Qualitative interpretations of cross-border effects from impacts in Central Asia to the EU for migration for the four SSP-based scenarios in the EUx case study. Red colour indicates a decrease, and blue colour indicates an increase, with the deeper shades of colour and thicker trend lines showing a higher magnitude of change. The end of the century time slice determines the colour. The arrows are approximations of the direction of change over time.

Indicators	**Utopistan (SSP1 x RCP4.5)**	**Regional Rivalry (SSP3 x RCP8.5)**	**A Game of Elites (SSP4 x RCP4.5)**	**Fossil-Fuelled Development (SSP5 x RCP8.5)**
Skilled migration/ exchanges between Central Asia and EU				
Forced migration & refugee movement from C Asia to EU				

7. Discussion

This deliverable report has compared modelling results in two ways: (i) across the different scales of the case studies; and (ii) across the different types of impact models. The benefits of undertaking cross-sectoral, cross-scale and inter-model comparisons are discussed further in Sections 3-6 of this report. The cross-scale comparison identified commonalities as well as diverging trends in the projected development of certain indicators under different integrated climate and socio-economic change scenarios. The analysis showed that the magnitude, and in some cases the direction of change, differs across scale, highlighting that context-dependent solutions to climate change impacts are important. Inter-model comparisons help to provide a fuller picture of the impacts that might be expected under high-end climate change, as relying on one model alone for understanding such a complex issue as climate change impacts is limited by model uncertainty. By employing a variety of models and comparing the results, it is possible to identify areas of significant agreement between models, as well as significant model differences and hence uncertainty.

By using cross-scale as well as inter-model comparisons it was possible to create a much fuller picture of climate change impacts across Europe. Providing an overview of some of the potential future impacts under high-end climate change can enable decision-makers to undertake adaptation and mitigation efforts, despite the complexity of climate change. Modelling climate change impacts is full of uncertainties, but this study helps to provide a basis for decision-makers to overcome the barrier of the "unknowable" (Dunford et al., 2014).

7.1. Cross-scale synthesis of impacts

The results presented here show that the realisation of certain scenario combinations will have detrimental effects, but that their intensity will be spatially determined. Land use and crop yield indicators show strong agreement across all case studies in both direction as well as magnitude of impact. However, the magnitude of change for the Scottish case study is generally lower across all indicators than in the other regions, with the only exception being crop yields, where barley and wheat are projected to increase in Scotland across all scenarios rather than only under SSP4 and SSP5.

Forestry indicators also show general agreement across scales. In Iberia, changes over time in the unmanaged forest indicator are more varied than in the other cases. However, change at the end of the 21st Century still follows the direction of the other cases.

The synthesis of the water indicators indicates that Scotland will not experience much change in this sector. Iberia, by contrast, will be negatively impacted, particularly with regards to water availability, and the vulnerability to water exploitation will increase in this region. This is the sector with the least agreement in impacts across scales.

The heat mortality indicators also show similar developments across case studies. Within all cases, the population over 75 years of age will be most severely impacted by heat stress. This effect is strongest in Hungary. Scotland will not little change in heat related mortality.

7.2. Model uncertainty

It is important to consider the uncertainties associated with model analyses, in order to express the level of confidence in specific findings. This is especially important for cross-sectoral, integrated studies, which are tackling complex and sometimes poorly understood issues. There are a number of sources of uncertainty in such studies, including:

- **Impact model uncertainty**. This reflects the capacity of models to represent real-world processes, at an acceptable level of realism (see Section 3 for further discussion of impact model uncertainties). It also refers to how well models are able to represent adaptation processes, since such processes are underpinned by the uncertainties of human decision-making.
- **Emissions scenario and climate model uncertainties**. These uncertainties lead to uncertainties in impact model outputs that use climate data as inputs (see Sections 3-6). The uncertainties arise from the capacity of models to appropriately represent the climate system, and the uncertainty in inferring climate sensitivity.
- **Socio-economic scenario uncertainties**. These uncertainties reflect the difficulties in quantifying socio-economic parameters within scenarios (e.g. population, GDP), as well as the difficulties in describing the process interactions within narrative storylines, realistically.
- **Error propagation uncertainties**. In cross-sectoral, integrated models (e.g. the IAP2), errors and hence uncertainties can propagate through models from one sector to the next. This could lead to the amplification of uncertainties.
- **Agent-based model uncertainties (ABMs).** ABMs in particular seek to represent human behaviour and decision-making (e.g. CRAFTY), which is difficult to do given the lack of general theories of human behaviour.

There are also some specific sources of uncertainty relating to the choices made in the design of the project:

- **No modelling of extreme weather events** (with the exception of high flow events), which are likely to increase. This means that certain positive impacts, such as increases in crop yields or forest productivity, might be negated by extreme weather events such as droughts or extreme wet phases. Even models with a daily time-step are unable to simulate extremes if the climate scenarios used as input to the models do not account for variability.
- **Uncertainties related to impacts across scales**. This is of particular concern for climate change as interconnections across regions make it difficult to pin-point sources of impacts. On the

other hand, actions in one region might have unintended impacts elsewhere. To deal with this issue, the EUx case study was included to analyse to what extent the impacts of climate change in a region outside the EU and their consequences for the EU can be identified.

Recognising and highlighting uncertainties in models is important, as a lack of knowledge about uncertainties could act as a constraint to effective adaptation decisions. This does not mean that decisions are not made when outcomes are uncertain. Decision-makers are constantly faced with uncertainty, and generally are able to make decisions with uncertainty (see Deliverable D2.1 [Dzebo et al., 2015]). However, as Dunford et al. (2014) point out, it is important to inform decision-makers of the nature of these uncertainties. This enables informed decision-making on their part, and allows them to base adaptation decisions on models they choose to trust. Informing decision-makers of model uncertainties can therefore promote a proactive approach to climate change adaptation.

The quantitative inter-model and cross-scale comparison (Section 3) has highlighted a few model-specific uncertainties that can be informed by inter-model comparisons. By using different models contemporaneously, or by using information from one model to improve another model's outputs, it was possible to identify results that have a higher degree of confidence. This is particularly important for decision-makers. This was evidenced in the case of crop yields, where the imposition of a non-zero IAP2 mask on the ISIMIP data resulted in the ISIMIP results resembling more closely the IAP2 results. This highlights how the characteristics of the ISIMIP models of allocating crops to every grid-cell instead of growing them only in the most profitable and climatically appropriate regions, as is done by the IAP2 model, can result in artificially lower crop yields.

Rather than revealing a particular issue that could be resolved by including different parameters, the comparison of water models (SWIM and WGMM) indicated that the models had strengths and weaknesses with regards to certain issues. For instance, SWIM modelling of climate change impacts might be more reliable, while WGMM produces better outputs for high river flows. This stresses the advantages of using a variety of models to account for strengths and weaknesses and the related uncertainties of different models.

In other cases, such as for the forest productivity modelling, the inter-model comparison did not serve to directly compare results across models, as the models were based on distinctly different assumptions. However, the comparative exercise did in this case serve to create a richer picture of forests in Europe under different climate scenarios, exemplifying another path for overcoming model uncertainties.

The CRAFTY-IAP2 comparison of land-use indicators not only highlighted how modelling assumptions can contribute to vastly different outcomes (thereby becoming a significant source of model uncertainty), but also highlighted the need to further investigate assumptions of economic rationale in decision-making of land use change as well as actor heterogeneity.

Differences between the rIAM and IAP2 models on population growth and the development of urban areas underline uncertainties caused by different input data. The different datasets on population used by the two models, as well as different ways of handling these data, contributed to different modelling outcomes for comparable indicators.

The use of integrated assessment models (IAMs), despite the uncertainties associated with them, provides a much fuller picture of cross-sectoral climate change impacts and highlights feedbacks between sectors. By comparison, single-sector model runs are less effective in providing outputs for interconnected sectors and less adapt at capturing the impact of socio-economic drivers that affect multiple sectors simultaneously. They are also less able to capture feedbacks between different sectors (Harrison et al., 2016). To enable effective decision-making, the use of single-sector models (which provide detailed outputs for one specific sector, but are less able to capture cross-sectoral interconnections) in combination with IAMs is therefore preferred. In this way, sector-specific processes can be identified via single-sector models, while the IAMs provide a better systemic understanding of cross-sectoral interactions and feedbacks. In addition, and of great importance, our results demonstrate that consideration of plausible alternative socio-economic scenarios can lead to much greater differences between model outcomes than focusing on climate scenarios alone.

Furthermore, it is important to recognise the extensive testing that has gone into the modelling tools used in IMPRESSIONS, including sensitivity analysis through the IRS method. Remaining uncertainties should therefore not become a barrier to proactive decision-making on climate change mitigation and adaptation (Brown et al., 2015). The models should be seen as tools, and, as their output shows, socio-economic decisions are imperative in shaping the effects of climate change. Uncertainties aside, this result should be seen as the key driver to take climate change adaptation forward. Some of the limits of adaptation measures are highlighted in the next section.

7.3. Limits to adaptation

Modelling climate change impacts is important as the results (can) form the basis for decisions on adaptation measures as well as improving adaptation outcomes. However, the review by Holman et al. (2018), conducted within IMPRESSIONS, has highlighted current inadequacies in the way that adaptation is generally represented within land and water sector models. By using an integrated assessment approach, some of the barriers to adaptation often highlighted in the literature can be overcome. Adaptation to climate change is a reaction to changed circumstances, and refers to the necessary adjustments to deal with harmful, as well as beneficial, impacts of said changes (Adger et al., 2008), or "means of reducing future vulnerability to climate conditions and extremes (through reducing exposure or sensitivity or increasing coping capacity)" (Tinch et al., 2015, p. 337). It is possible to differentiate between types of adaptation: incremental change, where changes are slowly implemented; or transformative changes, which implement radical and swift change (Adger et al., 2015). These forms of change are highlighted in the discussion of pathways in Deliverable D4.2 (Hölscher et al., 2017), where adaptation pathways are differentiated from transformation pathways. When it comes to societies' adaptive capacity (the ability to carry out adaptation measures), the approach taken in IMPRESSIONS conceptualises this as a related, but distinct, concept from coping capacity, which rather focuses on the ability to deal with changes when they actually occur. In particular, adaptive capacity within the IAP2 is a function of the availability of relevant capitals (social, human, manufactured and financial) and the socio-economic scenario context, allowing adaptive capacity (and the effectiveness of adaptation) to differ between socio-economic scenarios and between different types of adaptation (e.g. technological, environmental, social). A clear distinction has practical implications by helping to "strike a balance between a focus on technological solutions and the consideration of social and economic context" as well as ensuring that sufficient attention is paid to the instantaneous coping element (Tinch et al., 2015, p. 337).

Not all adaptation measures result in immediate positive outcomes, and different adaptation measures might influence each other. Different combinations of adaptation measures, therefore, do not automatically result in an immediate amelioration of climate change impacts or a reduction in exposure. Under certain circumstances, the number of people vulnerable to climate change impacts might even increase (Jaeger et al., 2014). Vulnerability is defined as "the threat of possible future harm to human well-being" and "a society is considered to be vulnerable when the impacts are beyond its capacity to cope" (Jaeger et al., 2014, p. 399), where this vulnerability can be conceptualised as low coping capacity[3].

As highlighted in the previous section, model uncertainties should not be seen as a barrier to adaptation, but rather as opportunities for informed decision-making. This is also supported by Adger et al. (2008), who argue that uncertainty about the future and limited foresight should not be seen as a limit to what adaptation measures can be taken now. The modelling undertaken in the IMPRESSIONS project overcomes this issue by providing outcomes for different combined climate and socio-economic scenarios. This enables decision-makers to choose adaptation measures that appear robust in different scenarios. The development of pathways for the different scenarios supports such decision-making, as there are certain topical pathways that appear across scenarios. In addition, the pathways also support context-specific adaptation measures to take place. This has been explored in greater detail in Deliverable D4.2 (Hölscher et al., 2017), where the scenario-specific effectiveness of adaptation measures within the pathways to achieve a pre-defined vision was assessed using the IMPRESSIONS models. Context-specific adaptation measures are a factor that enables the overcoming of a further limit to adaptation often highlighted in the literature: an overly technological approach to adaptation that discounts social as well as cultural context (Eriksen et al., 2011).

The need to incorporate social context has been achieved in the IMPRESSIONS project by co-developing scenario narratives with key stakeholders. The case study specific scenarios highlight different priorities when simulated by the IMPRESSIONS IAP2 dependent on the different contexts. This manifests as scenario-specific differences in the plausible implementation of adaptation options that influence the ability to meet the European vision by 2100 (Hölscher et al., 2017). This serves to highlight that adaptation decisions will be dependent on what is perceived as either a manageable risk that it is possible to adapt to or what is perceived as a change that might actually be welcome. At the same time, if a certain impact is seen as changing society to such an advanced degree that it might become unrecognisable, it is likely that a limit to adaptation will have been reached and no further action will be taken (Adger et al., 2008). In this case, rather than exhausting adaptation measures when faced by severe impacts, the perceived changes are so severe that the values and norms of the affected society are unable to deal with them, resulting in no adaptation measures being taken. The role of values and norms in determining which changes are seen as losses by society, and which are seen as opportunities, should therefore not be discounted.

8. Conclusions

This deliverable has presented results from a range of sectoral inter-model and cross-scale comparisons. Quantitative comparisons have been presented and analysed for a limited number of models with consistent impact indicators, and a more comprehensive qualitative comparison across models, scales and sectors has been presented in the form of synthesis tables.

[3] The IPCC 5th Assessment Report (AR5) definition of vulnerability focuses on contextual (usually social) vulnerability. Vulnerability in IMPRESSIONS is used more along the lines of the IPCC AR4 definition, which relates to vulnerability as an outcome. The IAP2 and rIAM models include the concept of capitals that are combined into a measure of (outcome) vulnerability. In the IPCC AR5 definitions, this is defined as "risk" in which (contextual) vulnerability interacts with the hazard (climate and related environmental changes/events) and with exposure to these hazards to produce "risk".

The IMPRESSIONS case studies have advanced understanding of CCIAV for high-end scenarios and also made strides in addressing model uncertainty through the work on improving European-scale models, such as the CLIMSAVE IAP (resulting in the European and Scottish IAP2) and developing new European-scale models, such as rIAM and CRAFTY. This was supplemented by more detailed CCIAV modelling at regional and local scales using a variety of physical, statistical and agent-based models. The results from this work demonstrate the significant impacts and vulnerabilities that are likely to arise from high-end scenarios, but also some of the opportunities afforded through adaptation, land-based mitigation (bioenergy and reforestation) and transformation.

The cross-scale comparison also highlighted the benefits of looking at different scales within one project, as this can reveal important variations. Impacts are spatially and temporally variable, as demonstrated by the synthesis tables in this deliverable. Certain regions of Europe will be impacted more negatively by climate change while others might benefit. In addition, using cross-sectoral modelling approaches has also been shown to have significant benefits over single-sector models. Only by integrating different sectors can model outcomes portray the connections and feedbacks between different sectors. Integrated models are also better able to reflect socio-economic scenarios, as highlighted in the discussion because they account for indirect effects and relationships between drivers. This is particularly recognisable in the IAP2 results for agriculture and forestry.

There remains, however, much to be explored. It is important to continue testing and improving CCIAV and integrated assessment models. In addition, further case studies of regions in Europe not covered in the IMPRESSIONS project might be beneficial and reveal new insights into regional variations and priorities. In addition, the Central Asia (EUx) case study has highlighted the need to explore further cross-border impacts, both impacts the EU has on other regions in the world, but also external factors influencing climate change impacts within the EU.

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Appendix A

Table A1: Impact and adaptation models used in IMPRESSIONS: their type, sectoral coverage, applications in the project, and the case studies in which they were applied. Modified from Carter et al. (2015).

Model	Type	Sectoral coverage	Analysis	Case study
AIM/Impact[Health]	STA*	Human health	S, I, C	Glo, Eur, EUx
AIM/Impact[Water]	PRB*	Water resources	C	Glo
M-GAEZ	PRB*	Agriculture	I	Glo
VISIT	PRB*	Biodiversity	I	Glo
GLOBIO	IND	Biodiversity	S, I, C	Glo EUx
WaterGAP2	PRB	Water resources	S, I	Glo, Eur, EUx
iPETS	IAM	Multi-sector; population	S	Glo, Eur, EUx
DSK	ABM	Macroeconomy; energy	P	Glo, Eur
IMAGE	IAM	Agriculture, Land-use	C	Glo
LAGOM	ABM	Production, consumption	S	Eur
CRAFTY 1.0	ABM	Land use	I, C	Eur
IAP2	IAM	Multi-sector	S, P, C	Eur, Sco
rIAM	IAM	Multi-sector	S	Eur
SFARMOD	ECO*	Agriculture	S, I, C	Eur, Sco
ForClim v3.2	PRB	Forest productivity	S, I, C	Eur, Sco
CFFlood Model	PRB*	Coastal and pluvial flooding	S, I	Eur, Sco
WaterGap meta-model (WGMM)	EMU*	Water resources	S, C	Eur, Sco
SPECIES	STA*	Biodiversity	S	Eur, Sco
RUG	CA	Population, urbanisation	S	Eur
Heat-mortality (HEET)	STA	Human health	S	Eur, Hun
SWIM	PRB	Hydrology	S, P, C	Eur, Ibe, Sco, Hun
APORIA	ABM	Agricultural land use	S	Hun
LandClim v1.4	PRB	Forest landscape	S	Ibe
Lyme disease (LYM)	CEL	Human health	S	Sco, Hun
ALLOCATION	DEM	Population, urbanisation	S, C	Hun
SWAT	PRB	Water resources	I	Ibe

Type of model: ABM=agent-based; CA=cellular automata; DEM=demographic; ECO=economic; EMU=process-based model emulator; IAM=integrated assessment; IND=indicator-based; PRB=process-based; STA=statistical; *=component model of an IAM.

Type of analysis conducted: S=scenario runs for case studies; P=adaptation pathway analysis; I= impact response surface (IRS) analysis; C=comparison of models.

Case study: Eur=European Union 28 + Norway and Switzerland; EUx=EU external (Central Asia: Kazakhstan, Kyrgyzstan, Tajikistan, Turkmenistan and Uzbekistan); Glo=global; Hun=Hungary; Ibe=Iberia; Sco=Scotland.