Climate Change Impacts, Adaptation and Vulnerability Model Applications in Three Regional to Local Scale Case Studies in Europe

Deliverable D3C.2

July 2017

Liz Clarke[1], Mark Rounsevell[1], Miriam Dunn[1], Tiago Capela Lourenço[2], David Tàbara[3], Laszlo Pinter[4], Linda Juhasz-Horvath[4], Zsofi Gaál[4], Ian Holman[5], Niki Frantzeskaki[6], Jill Jäeger[7], Jens H. Christensen[8], Marianne Sloth Madsen[8], Simona Pedde[9], George Cojocaru[10], Anastasia Lobanova[11], Sen Li[12], Harald Bugmann[13], Rebecca Snell[14], Valentine Lafond[13], Paula A. Harrison[15], Stefan Fronzek[16], Kiyoshi Takahashi[17], Yasushi Honda[17], Akihiko Ito[17], Akemi Tanaka[17], Minoru Yoshikawa[17] and Victoria Janes[5]

[1] University of Edinburgh, UK
[2] Fundacao da Faculdade de Ciencias, Universidade de Lisboa, Portugal
[3] Independent, Spain
[4] Central European University, Hungary
[5] Cranfield University, UK
[6] Dutch Research Institute for Transitions, Netherlands
[7] Independent, Austria
[8] Danish Meteorological Institute, Denmark
[9] Wageningen University, Netherlands
[10] TIAMASG Foundation, Romania
[11] PIK, Germany
[12] University of Oxford, UK
[13] ETH-Zurich, Switzerland
[14] University of Ohio, USA
[15] Centre for Ecology & Hydrology, UK
[16] SYKE, Finland
[17] The University of Tsukuba, Japan

Prepared under contract from the European Commission
Contract n° 603416
Collaborative project
FP7 Environment

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

Deliverable title:	Regional/local scale CCIAV appplications

Deliverable n°:	D3C.2
Nature of the deliverable:	Report
Dissemination level:	Public

WP responsible:	WP3C
Lead beneficiary:	University of Edinburgh (UEDIN)

Citation:	Clarke, L., Rounsevell, M., Dunn, M., Capela Lourenço, T., Tàbara, D., Pinter, L., Juhasz-Horvath, L., Gaál, Z., Holman, I., Frantzeskaki, N., Jäger, J., Christensen, J.H., Madsen, M.S., Pedde, S., Cojocaru, G., Lobanova, A., Li, S., Bugmann, H., Snell, R., Lafond, V., Harrison, P.A., Fronzek, S., Takahashi, K., Honda, Y., Ito, A., Tanaka, A., Yoshikawa, M. and Janes, V. (2017). Climate Change Impacts, Adaptation and Vulnerability Model Applications in Three Regional to Local Scale Case Studies in Europe. EU FP7 IMPRESSIONS Project Deliverable D3C.2.

Due date of deliverable:	Month n° 45
Actual submission date:	Month n° 45

Deliverable status:

Version	Status	Date	Author(s)
1	1st draft	31 May 2017	Clarke et al.
2	2nd draft	3 July 2017	Clarke et al.
3	final	30 July 2017	Clarke et al.

Contents

Summary

This deliverable report (D3C.2) presents the analysis of high-end climate change impacts, adaptation and vulnerability in the IMPRESSIONS regional/local case studies of Hungary, Scotland and Iberia. A wide range of climate change impacts, adaptation and vulnerability (CCIAV) models were applied in the case studies and these were selected to match the key high-end climate change challenges that were defined in consultation with local stakeholders. The models were applied to integrated climate and socio-economic change scenarios to 2100 that combine the Representative Concentration Pathways (RCPs) and Shared Socio-economic Pathways (SSPs). The intermediate climate change scenario (RCP4.5) was combined with SSP1 (*Sustainability*) and SSP4 (*Inequality*), since these socio-economic pathways envisage lower challenges to climate mitigation. The high-end climate change scenario (RCP8.5) was combined with SSP3 (*Regional Rivalry*) and SSP5 (*Fossil-fuelled Development*), since these socio-economic pathways envisage high challenges to climate mitigation. All case studies modelled land resources with Hungary and Scotland addressing urban and agricultural land use, and Iberia and Scotland addressing forestry or agro-forestry. All case studies covered issues related to water resources including water stress in Iberia and Hungary and flooding in Scotland. In addition, Hungary and Scotland assessed impacts on human health and well-being, in particular Lyme disease risk, and in Hungary only, heat-related mortality.

Hungary is already experiencing the effects of climate change: seasons are shifting and extreme weather events are becoming more frequent with heat waves, extreme droughts and flooding. The CCIAV modelling projected increased vulnerability to high-end climate change for agricultural land use, water availability and human health. In particular, the population are highly vulnerable to increases in extreme heatwaves resulting in large rises in daily mortality. Heat stress and water stress will have a major impact on agricultural production, although shifts in agricultural land use are affected by many climate and socio-economic factors. The increase in warm days coupled with a lack of freshwater are critical constraints, which ultimately will hinder agricultural productivity and food security.

The CCIAV modelling for Scotland projected that landscape configuration will alter as a consequence of future climate and socio-economic change. Significant changes in land use patterns and hydrological flows in the future have the potential to influence society's ability to balance food production, biodiversity protection and ecosystem service provision. A changing climate could present opportunities to modify forest species and/or produce new agricultural crops. However, high-end climate change will also change the way society interacts with landscapes. For example, key influences were found on cultural ecosystem services and the Scottish tourism sector, including the perception of the changing aesthetic quality of landscapes and the increasing risk of Lyme disease.

The Iberian Peninsula (and the Tagus river basin area in particular) was projected to continue the current trend towards a drier and more vulnerable landscape. Seasonal climate variability is expected to play a major role in the impacts of high-end climate change since current water resources and agroforestry management are highly dependent on accumulated precipitation during the hydrological year (October to September), in particular during the wet period (October to April). Increasing drought frequency and intensity was projected to negatively influence the provisioning of multiple ecosystem services related to agro-forestry and water resources. High-end climate change will, thus, prompt the need for changes in land use planning and the consideration of novel management options.

Across the case studies, impacts were less severe under intermediate (RCP4.5) than high-end (RCP8.5) climate change. However, impacts under RCP4.5 were often still highly detrimental, particularly for

water availability in Iberia and heat stress in Hungary. Impacts were generally less negative under the sustainability-focused SSP1 scenario compared with the highly fragmented SSP3 or fossil-fuel intensive SSP5 scenarios. For example, SSP1 resulted in moderate increases in compact urban development patterns, whilst SSP5 resulted in large increases in sprawled urban development in both Hungary and Scotland. Similarly, increases in heat-related mortality in Hungary were least under SSP1 and greatest under SSP5, although this was due to a mix of socio-economic and climate effects. Likewise, for Iberia, water availability decreased the least under SSP1 due to advances in the efficiency of water withdrawals and more efficient water use, and decreased the most under SSP3 and SSP5 due to increased water withdrawals and the severe impacts of high-end climate change on water availability.

Cross-sectoral vulnerabilities were found to be highly dependent on the socio-economic scenario with each narrative based on different assumptions about how society manages land, water and energy resources and their competing demands. This includes what resources are prioritised, for example between food production, forestry, biodiversity protection and ecosystem service provision, and how trade-offs can be balanced. The impacts under the four integrated scenarios show that the choices made by decision-makers and societal actors will lead to large differences in future impacts. These differential impacts demonstrate the range of both opportunities and potential risks associated with high-end climate change and can aid stakeholders, by informing discussions, in exploring potential adaptation and mitigation pathways.

1. Introduction

Deliverable D3C.2 reports on the advancement and application of regional/local scale methods and models for quantifying climate change impacts, adaptation and vulnerability (CCIAV) associated with high-end climate and socio-economic scenarios. The outcomes of this work are described for the three regional/local case studies within IMPRESSIONS (Hungary, Scotland and the Iberian Peninsula), covering a range of key economic, social and environmental sectors and their cross-sectoral interactions. The specific themes and research questions are different across the three regional/local case studies and, hence, methodological and modelling approaches differ between them. Where process-based models do not exist for some sectors in a region then outputs from the European scale modelling (see Deliverable D3B.2 - Holman et al. 2017) have been downscaled to the regions and combined with qualitative methods.

The research in Work Package (WP) 3C links closely with WP2 which provided the regional/local scale climate and socio-economic scenarios which have been applied to the modelling approaches (see Deliverables D2.2 - Kok and Pedde 2016 and D2.3 - Madsen et al. 2016). It also provides inputs to WP4 which is developing the participatory adaptation and mitigation pathways, and WP5 which is synthesising all the outputs from IMPRESSIONS within the Information Hub to explore transformative strategies for coping with high-end climate change. The global (WP3A) and European (WP3B) case studies have provided boundary conditions for the three regional/local case studies (see Deliverables D3A.1 – Carter et al. 2016 and D3B.2 – Holman et al. 2017, respectively). In particular, the land use change projections derived from the European modelling have provided input to more detailed, process-based models of individual sectors within the regional/local case studies.

2. Methods for regional/local scale CCIAV modelling

2.1. Description of the case studies

IMPRESSIONS focuses on three regional/local scale case studies covering different parts of Europe (central – Hungary; northwest – Scotland; and Mediterranean – Iberia) and different scales of assessment (national – Scotland; transnational river basin – Iberia; and local municipalities – Hungary). Details of each case study are given in the following section.

2.1.1. Hungary

The Hungarian case study focuses on two local communities, Szekszárd and Veszprém (Figure 2.1), and three major topic areas, urban and agriculture land use, water availability, and human health. Through extensive modelling and stakeholder engagement, the study aims to test the ability of existing development strategies and adaptation plans to reduce vulnerability and increase resilience to high-end climate and socio-economic change. This information will help relevant stakeholders to develop effective integrated mitigation and adaptation solutions, transformative strategies and transition pathways.

Hungary is located in the Carpathian basin, where the number and intensity of extreme climate events have increased over recent decades – especially droughts, floods, heavy rainfalls and heat waves. There is also a clear increasing trend in annual average surface temperatures, in line with climate model projections (Second National Climate Change Strategy, 2017). Such projections suggest that Hungary may be one of the most vulnerable countries to climate change in Europe, particularly in terms of increasingly intense and frequent extreme weather events (Second National Climate Change Strategy, 2017).

With over 500,000 farms and half of its territory being used as farmland (Central Statistical Office, 2016), Hungary is a predominantly agrarian country, which makes it particularly vulnerable to high-end climate change. In addition, urban environments are also expected to be affected by high-end scenarios, particularly in terms of heat stress and human health. Furthermore, there are many existing regional inequalities, such as the urban-rural divide and the rich-poor divide, which may worsen under high-end climate change. The Hungarian case study aimed to map these local risks and vulnerability hotspots in the two medium-sized communities of Szekszárd and Veszprém in consultation with local stakeholders and decision-makers.

Figure 2.1: The two case areas, Szekszárd and Veszprém, are located in the Transdanubian region of Hungary, close to the Lake Balaton, the largest freshwater lake in Central Europe.

2.1.2. Scotland

The Scottish case study focuses on the national scale (Figure 2.2) and explores the risks posed by high-end scenarios for land and water resource sectors, including forestry, agriculture, tourism, health and river flows. The issues analysed in the Scottish case study centre around the attitudes and decision-making of key Scottish stakeholders for climate change adaptation. These themes were identified in a series of interviews with key stakeholders (Dunn et al. 2017). They include the potential implications of: (i) Scotland's reforestation targets; (ii) changing growth patterns for commercial tree species; (iii) potential changes to tourism activity; (iv) changing hydrological patterns and their implications for aquatic ecosystems; and (v) the implications of future land use/climate on the risk of Lyme's disease. The outcomes of the study aim to provide new evidence to support the Scottish Adaptation Strategy and Land Use Strategy, as well as to support decision-makers in incorporating high-end scenarios into their risk management strategies.

Scotland has a highly ambitious climate change adaptation policy, implemented through the Climate Change Act of 2009 and the associated Climate Change Adaptation Programme and Climate Change Adaptation Framework. The Scottish Government's Climate Change Adaptation Framework and associated Sector Action Plans provide information on the impacts and options for adaptation within Scotland. Sector Action Plans outline the government's priorities and planned adaptation actions.

The Scottish Government's Climate Change Adaptation Framework and Sector Action Plans have paved the way for substantive organisational research within the climate change arena in Scotland. Numerous organisations are currently implementing internal policy changes based on the business risks and opportunities posed by climate change. These organisations are cross-sectoral and include: government; non-governmental organisations; industry; research; and academic institutions. The policy changes taking place within these varied organisations are indicative of the progressive status of climate change adaptation research within Scotland.

Figure 2.2: Map showing the location of the Scottish case study within Europe (highlighted in red inside the red box; left; Google, 2015) and a detailed breakdown of the local authority areas within Scotland (right; Scottish Government website[1]).

2.1.3. Iberia

The Iberian case study focuses on a transnational river basin and issues related to water and land management in the Mediterranean region. The river basins of the Iberian Peninsula are among those in Europe most likely to be affected by climate change, especially under high-end scenarios. The Tagus river basin (Figure 2.3) is one of the five international river basins shared between Portugal and Spain, posing multiple challenges for the management of shared water resources and for the coordination of sensitive social-ecological systems, both potentially intensified under high-end climate change. Water scarcity is likely to be aggravated by the traditional focus on irrigation - the main source of water demand on both sides of the river basin - as well as by growing urban water demand and large-scale water transfers. Sectors of societal importance such as agriculture, forestry, energy production and nature conservation, along with activities carried out along the river basin, may become more vulnerable to land use pressures acting upstream of the basin.

The dry landscapes of southern Spain and Portugal, including the Tagus river basin, are home to the unique oak-grassland agroforestry systems known as "Dehesa" (Spain) or "Montado" (Portugal). These systems may be especially vulnerable to climate change because of the projected increases in

[1] http://www.gov.scot/Resource/Doc/933/0009386.pdf [accessed July 2017]

drought frequency and intensity, but also due to changing socio-economic trends, for example, a decline in the demand for cork.

Figure 2.3: The Tagus transboundary river basin.

Understanding the main drivers and barriers for adaptation-related decision-making and improving institutional cooperation can be seen as some of the most important, and potentially fruitful, strategies to confront the expected impacts of high-end climate change. The main goal of the Iberian case study is to develop transformative solutions to cope with high-end scenarios in the Tagus river basin. In particular, working with decision-makers, the case study explores two types of systemic solutions: (i) Integrated River Basin Management, to explore different policy mixes at the river basin scale, including the interactions between water, energy (hydropower) and land use management, and to assess how to improve the resilience of socio-ecological systems; and (ii) Ecosystem-Based Approaches on the Dehesa/Montado agroforestry systems, to look at the conditions necessary for improving the resilience and productivity of these ecosystems and landscapes, including how to enhance ecosystem services and the livelihoods of populations at the local scale (e.g. farm level).

2.2 Climate and socio-economic scenarios

2.2.1. Climate scenarios

A subset of CMIP5 global climate model (GCM) simulations were selected for use in IMPRESSIONS based on the recent set of IPCC emissions scenarios (the Representative Concentration Pathways, RCPs). The models were selected to represent changes in global mean temperature between approximately 2°C and 4°C (based on RCP4.5 and RCP8.5), but with relatively more models representing high-end climate change. Only GCM simulations that had been dynamically downscaled in CORDEX were included in the subset so that the regional and local case studies could make use of the higher resolution data from the regional climate models (RCMs). The RCP and climate model selection criteria are described in detail in Deliverable D2.1 (Kok et al., 2015). The spread in local and regional temperature and precipitation changes, represented by the selected subset of RCP x GCM-RCMs, is shown in Table 2.1.

Details of the method for creating the climate scenarios based on these GCM-RCM combinations is provided in Deliverable D2.3 (Madsen et al., 2016). The same deliverable also presents maps of projected changes in temperature, precipitation, solar radiation, wind speed and relative humidity for each of the selected RCP x GCM-RCMs in Europe.

Table 2.1: Changes in temperature (ΔT) and precipitation (Δpr) (2071-2100 vs. 1961-1990) for each of the case study regions for each of the selected RCP-GCM-RCMs in the core set. Note: Only land-based points are included.

Emission Scenario	GCM	RCM	Europe ΔT/Δpr	Scotland ΔT/Δpr	Iberia ΔT/Δpr	Hungary ΔT/Δpr
RCP8.5	HadGEM2-ES	RCA4	5.4°C +5%	3.8°C +8%	5.5°C -27%	5.1°C +10%
RCP8.5	CanESM2	CanRCM4	5.4°C +8%	3.6°C +13%	5.6°C -19%	5.5°C +12%
RCP8.5	IPSL-CM5A-MR	WRF	4.7°C +13%	2.8°C +4%	3.8°C -23%	4.2°C +26%
RCP8.5	GFDL-ESM2M	RCA4	3.7°C +6%	1.7°C +14 %	3.4°C -18%	3.5°C +9%
RCP4.5	HAdGEM2-ES	RCA4	3.0°C +3%	2.2°C +6%	2.8°C -17%	2.5°C +11%
RCP4.5	GFDL-ESM2M	RCA4	2.2°C +3%	0.9°C +9%	1.9°C -7%	2.2°C +2%
RCP4.5	MPI-ESM-LR	CCLM4	2.0°C -4%	1.3°C +3%	2.2°C -19%	2.0°C -4%

2.2.2. Socio-economic scenarios

Socio-economic scenarios were created for the three regional/local case studies using participatory approaches in stakeholder workshops (see Deliverable D2.1 - Kok et al., 2015). The scenarios were based on the IPCC-related global socio-economic scenarios (the Shared Socio-economic Pathways, SSPs). These global scenarios were downscaled for Europe (Eur-SSPs) by mapping and matching them to existing European scenarios from the CLIMSAVE project (Harrison et al., 2015). As with the global SSPs, the European SSPs cover a wide range of the dimensions of sustainability and development, by including both highly unequal (SSP3 and SSP4) and equal societies (SSP1 and SSP5), but also very resource intensive (SSP5 and SSP3) and lower consumption worlds (SSP1 and SSP4).

Regional and local scenarios were developed from the Eur-SSPs as part of a stakeholder-led process (see Deliverable D2.2 – Kok and Pedde, 2016). For Iberia and Hungary, the Eur-SSPs provided the boundary conditions for developing the regional/local scenarios with stakeholders. For Scotland, the Eur-SSPs also provided boundary conditions, but as an existing set of CLIMSAVE scenarios was also available, these were matched to the SSPs and extended to 2100. SSP1 (Sustainability) and SSP3 (Regional Rivalry) matched well and SSP4 (Inequality) matched in part (Table 2.2). However, it proved difficult to match SSP5 (Fossil-fuelled Development) with the CLIMSAVE scenarios. Consequently, a Scottish version of this scenario was developed from the SSP storyline.

In all three case studies, the socio-economic scenarios include both qualitative descriptions and quantifications. Qualitative descriptions include narratives and tables that summarise trends in key elements; all of which were developed during the facilitated stakeholder workshops (see Deliverable D6A.2 - Zellmer et al. 2016 for details of the workshop processes). In addition to qualitative descriptions, the scenarios included two quantitative elements:

1. Direct stakeholder-led quantification of key model variables, analysed using a Fuzzy Sets approach (Deliverable D2.2 - Kok and Pedde, 2016; Pedde et al., in review);
2. Expert estimates based on the interpretation of the scenario narratives and tables.

Table 2.2: Mapping of CLIMSAVE scenarios for Scotland to the SSPs with illustrative examples for economic, environmental and social uncertainties.

Scenario	Economic	Environmental	Social	SSP
Tartan Spring	Strong but weakening	Weak environmental regulation	Disparate well-being	SSP4
Mad Max	Rollercoaster volatile	Non-existent	Disparate	SSP3
The Scottish Play	Gradual strong with blips	Trade-offs	Equitable	(SSP5)
MacTopia	Strong	Integrated	Equitable	SSP1

Quantifications of the scenarios are used as inputs to the CCIAV model applications. The stakeholder-led quantification focused on a limited set of scenario trends due to time limitations in the stakeholder workshops. Four model variables were selected for stakeholder quantification based on two criteria. First, the variables mirror the expertise of the majority of invited stakeholders and relate to the key issues for the case studies. Second, they provide guidance on the quantification of a much wider range of socio-economic variables used within modelling processes. In addition to these four model variables, stakeholders also quantified four capitals (human, social, manufactured and natural). Capitals are useful indicators of the overall ability of society to cope with, or adapt to, changing circumstances and thus avoid vulnerability (see forthcoming Deliverable D4.3 due September 2017). For more details on the stakeholder-led quantifications in each of the regional/local case studies see Deliverable D2.2 (Kok and Pedde, 2016).

The expert-based quantifications were undertaken by the IMPRESSIONS modellers, building on the guidance from the stakeholder-led process, and used to cover the wider range of variables required by each model.

2.2.3. Scenario integration

A full description, and justification, of the selected RCP × SSP modelling combinations (Table 2.3) utilised within the IMPRESSIONS case studies is presented in Deliverable D2.1 (Kok et al., 2015). The set of combinations used cover a range of possible high-end futures, including high-end climate change (RCP4.5 and RCP8.5) and a diverse set of socio-economic developments (SSPs 1, 3, 4 and 5), whilst being based on plausible RCP x SSP combinations.

Table 2.3: High-end RCP x SSP combinations utilised within the regional/local case studies.

Representative Concentration Pathway (RCP)	Shared Socio-economic Pathway (SSP)
RCP 4.5	SSP1
RCP 4.5	SSP4
RCP 8.5	SSP3
RCP 8.5	SSP5

2.3. Climate change impact models

A range of different modelling approaches were used in the regional and local case studies, including integrated modelling, process-based or physically-based modelling, and agent-based modelling. The following sections provide an overview of these different modelling approaches. Further information is given in Deliverable D3C.1 (Rounsevell et al., 2015).

2.3.1. Integrated modelling

The IMPRESSIONS Integrated Assessment Platform (IAP2) for Scotland was applied within the Scottish case study. This model represents a further development of the CLIMSAVE Integrated Assessment Platform (IAP) (Holman and Harrison, 2012; Harrison et al., 2015). The platform contains a series of linked sectoral models (Figure 2.4), which are described in Deliverable D3B.1 (Holman et al., 2015), but are briefly summarised here:

Urban: The Regional Urban Growth (RUG) meta-model (based on Reginster and Rounsevell, 2006) simulates the change in artificial surfaces for each NUTS2 region as a function of changes in the (i) population (total) and GDP (per capita), (ii) societal preferences (proximity to green space versus social amenities, and attractiveness of the coast), and (iii) strictness of the planning regulations to limit sprawl, assuming a fixed ratio of residential to non-residential urban areas. This function was calibrated from historical observational data across Scotland.

Water: The WaterGAP (WGMM) meta-model (Wimmer et al., 2015) uses 3D response surfaces to reproduce WaterGAP3 (Floerke et al., 2013). It runs at a 5' x 5' resolution for about 65 spatial units (single large river basins or clusters of smaller, neighboring river basins with similar hydro-geographic properties). The difference between simulated water availability (based on average river discharge Qavg) and projected non-agricultural water consumption determines the maximum water available for agricultural irrigation in each spatial unit.

Flooding: The Coastal Fluvial Flood (CFFlood) meta-model (Mokrech et al., 2015) is a simplified process-based model that identifies the area at risk of flooding based on topography, relative sea-level rise or change in peak river flow (derived using the median annual maximum flood discharge or QMED from WGMM) and the estimated standard of protection of flood defences. The probability of flood inundation constrains the allocation of land for agriculture, with land with a > 10% and > 50% annual probability of flooding being unsuitable for intensive agriculture and extensive agriculture, respectively, according to Mokrech et al. (2008).

Forest: MetaGOTILWA+ (Audsley et al., 2015) is an artificial neural network (ANN) that emulates GOTILWA+ (Gracia et al., 1999). The ANN was trained on GOTILWA results for 889 grid cells across Europe that captured the range of soil and climate variability in Scotland. It simulates average timber yields for a range of deciduous and coniferous tree species under different management regimes and soil characteristics.

Crops: The crop yield meta-models (Audsley et al., 2015) predict the average yield of a range of annual and permanent crops under rainfed and irrigated conditions. Those in the IAP2 have each been trained and validated on simulated outputs across Scotland from the daily ROIMPEL model (Audsley et al., 2006) for winter and spring wheat, barley and oilseed rape, potatoes, maize, sunflower, soya, cotton, grass and olives.

Rural land allocation: The SFARMOD meta-model (Audsley et al., 2015) allocates available land across Scotland based on profit and other constraints (urban land use, irrigation availability, food and timber demand). It uses a series of regression equations to simulate the behavior of the full SFARMOD-LP model, a mechanistic farm-based optimising linear programming model of long-term strategic land use. The meta-model was fitted to SFARMOD-LP outputs from 20,000 randomly selected sets of input data that fully cover the current and future parameter input space.

Biodiversity and habitats: The CFFlood meta-model (Mokrech et al., 2015) also simulates: change/loss in inland and coastal (inter-tidal, saltmarsh and coastal grazing marsh) habitats due to future climate and socio-economic conditions. The SPECIES model (Spatial Estimator of the Climate Impacts on the Envelope of Species) (Harrison et al., 2006) simulates the suitable climate space of over 100 species selected to interact with the agricultural, forest, coastal and water sectors. SPECIES also estimates a range of ecosystem services and evaluates the changing presence of appropriate conditions for a given species provided by appropriate climate space and appropriate climate and habitat space.

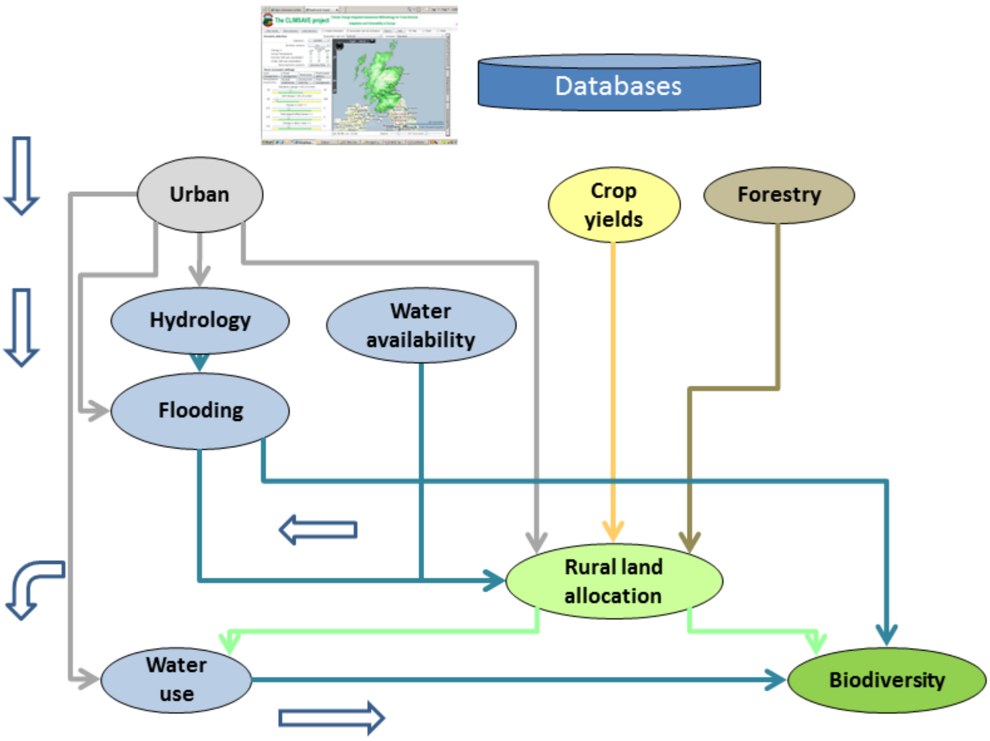


Figure 2.4: Schematic representing the cross-sectoral linkages between meta-models in the Scottish IMPRESSIONS Integrated Assessment Platform (IAP2).

2.3.2. Physically-based models

2.3.2.1. Forests

Two distinct forest models and simulation approaches were used for the Scottish and Iberian case studies. In Scotland, the research objective was to identify the species and locations where reforestation efforts could be focused in the future. The stand scale dynamic vegetation model 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 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.

For the Iberian case study, the research objective was to assess forest-related ecosystem service provision (e.g., production of cork, timber and livestock) under climate change, especially the increasing frequency and intensity of both drought and fire. The spatially-explicit landscape forest model LandClim (v1.6) (Schumacher et al., 2004) was used 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 (for example, planting more fire-tolerant and/or drought-tolerant species, protecting seedlings from grazing).

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 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.

In addition to simulating trees, LandClim also simulates the growth of a generic herbaceous layer. This herbaceous layer while referred to as "grass" is intended to encompass all herbaceous plant groups. Grass is represented as one cohort per grid cell. The biomass of the herbaceous layer is limited by the same growth-reducing functions as for trees, specifically temperature, light availability and water. Grass can reach its maximum biomass (set to 4 tons/ha in the current simulations, Sales-Baptista et al., 2015) in one year provided light, water and temperature are not limiting. If one or multiple factors are limiting, grass biomass is reduced by the most limiting factor. Grazing pressure is determined by the attractiveness of a cell to cattle. Cells that have higher grass production, are relatively flat, and have minimal tree cover are more attractive to livestock and thus have higher grazing intensities (Snell et al., 2017). High grazing intensities reduce tree establishment, lowering both the probability of establishment and the number of stems within a cohort. After a tree is established, grazing by cattle has no impact on tree growth or mortality.

It is important to recognize that neither the ForClim nor LandClim model is tuned to local data. LandClim aims to describe general relationships and thus can be applicable across a wide range of forests and landscapes. Equally, outcomes are emergent properties of the ForClim model, based on relatively simple assumptions about the influence of biotic and abiotic factors on trees and stand dynamics. As such, ForClim can be applied over a wide range of conditions and large geographical regions. When compared to ForClim and/or LandClim, it is possible that a statistical model, fitted to local data and local conditions, would, produce results that are more accurate. Results presented from the ForClim and LandClim models do not intend to predict the true volume of a forest or cork harvested (now or in the future), but rather to indicate trends and possible responses of forests to climate change. The advantage of both LandClim and ForClim, is that they can be used to simulate the response of forests to future climate conditions (which statistical models cannot reliably do).

2.3.2.2. Hydrology

The hydrological, process-based, basin-scale model Soil and Water Integrated Model (SWIM) was applied to all three regional/local case studies. The model showed a good fit between simulated and observed discharges, during both calibration and validation periods, in all three regions (Table 2.4). Within SWIM, it is possible to represent the water management infrastructure and therefore account for a subset of the components described by the socio-economic (SSP) narratives, particularly those that are connected to water withdrawals, water transfers, irrigation channels, reservoir construction and management.

Table 2.4: Results from two criteria of goodness of fit (the Nash-Sutcliffe efficiency and Relative Volume Error) for the calibration and validation periods for the case study river basins using the monthly time step.

River		Nash Sutcliff Efficiency	Relative Volume Error, %
Tay (Scotland)	Calibration	0.85	1.6
	Validation	0.88	1
Tagus (Iberia)	Calibration	0.82	15
	Validation	0.81	-12
Danube (Hungary)	Calibration	0.86	-4.6
	Validation	0.87	-5.9

Within the Scottish case study, the SWIM model was calibrated to the Tay river basin over the period 1984 to 2002. The model showed a very good fit to the observed values over the calibration and validation periods (Table 2.4). The model was set up for “naturalised” flow and did not include regulated lakes in the catchment.

Within the Hungarian case study, the SWIM model was applied to the entire Danube river basin. It was not possible to provide discharge estimations for the two selected communities (Szekszard and Veszprem), as the spatial extent under consideration was too small to support the setup of a hydrological model. Extensive irrigational channels characterise the Szekszard and Veszprem areas. It was impossible to include these irrigation channels into the modelling framework due to, again, a scale mismatch. Therefore, the results presented for this case study include only deviations in the discharge of the Zala river (the main tributary of Lake Balaton), as well as changes in runoff rates at the level of the Hydrological Response Units (elements within the model within which the hydrological cycle is calculated).

Within the Iberian case study, the SWIM model was applied to the entire Tagus river basin, taking into account major reservoirs (21 in total), large water transfers to the south of Spain (the Tagus Segura water transfer), and major intra-basin water transfers for irrigation and water supply (12 in total). The management of these man-made structures was altered to reflect the socio-economic (SSP) narratives. Operation of the Alcantara dam, which regulates hydrological flows between Portugal and Spain, was used as a proxy indicator for cooperation between the countries in terms of water resources.

2.3.2.3. *Heat stress mortality*

The modelling of heat-related mortality risks follows the approach developed for the European case study (see Deliverable D3B.2 – Holman et al., 2017). This model quantifies heat-related mortality under assumptions of climate change, population growth and ageing, and urban change for the following three age-groups: 0-64, 65-74, 75+ as risk increases greatly with age. The model uses inputs of population from the European version of the RUG urban model (see Section 2.3.1), with population attributable mortality being based on the method used by Vardoulakis et al. (2014).

Mortality data for Budapest was utilised in developing the temperature-mortality function as the populations of Veszprém and Szekszard are too small to provide meaningful estimates. This data was used to develop new exposure response functions based on the method of Gasperrini et al. (2010). This method better characterises the population response at the extreme end of the (exposure) temperature distribution, in order to capture the uncertainty in assessing impacts under high-end scenarios. The function was then applied to the RCP x SSP scenarios to calculate the annual number of heat-related deaths for Szekszárd (based on NUTS region HU23) and Veszprém (based on NUTS region HU21). In addition, changes in the frequency of heat alerts (average daily temperature at or above 25^{o}C for at least three consecutive days) and heat alarms (average daily temperature at or above 27C for at least three consecutive days) per decade were computed using RCM data for the two communities as indicators of health warnings for heatwaves.

2.3.2.4. Lyme disease risk

The Lyme disease risk (LYR) model (Figure 2.5) is a biological process-based, cellular automata model of the landscape-level distribution of ticks and pathogens. The model takes into account tick development, pathogen transmission, host population dynamics, as well as the influence of temperature (on tick population dynamics and the seasonality of host populations and their movement). The model was parameterised for, and applied within, both the Scotland and Hungary case studies. In both regions, the LYR model was utilised to predict the joint effects of temperature change, which directly influences tick and pathogen population dynamics, and land use change (taken from the Scottish/European IAP2 models) that shapes the suitability of habitats and the distribution of ticks.

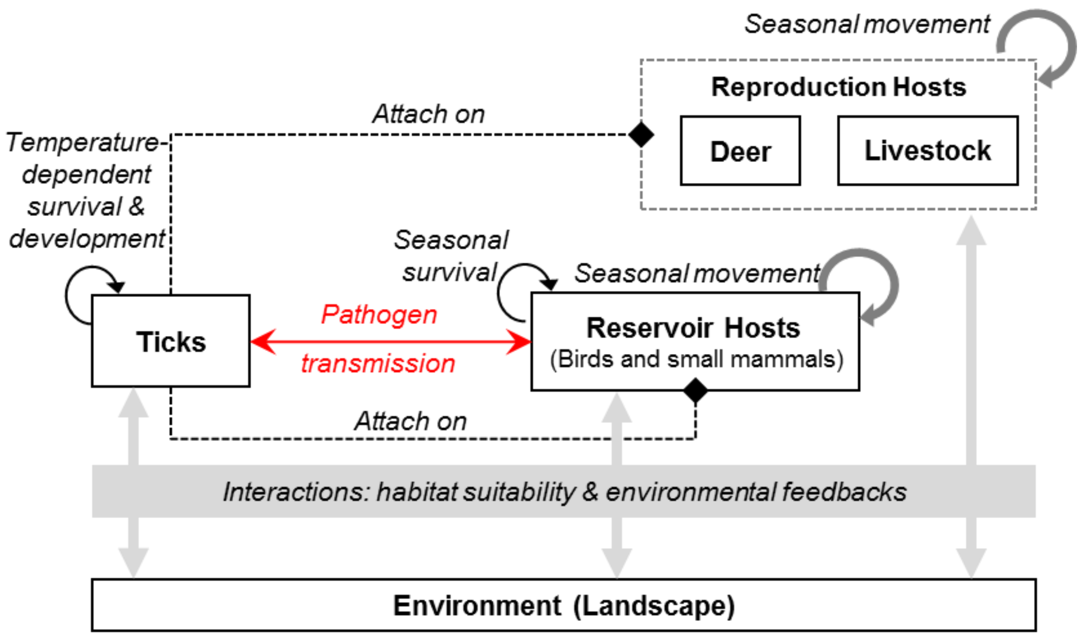


Figure 2.5: The LYR model framework: interactions between ticks, hosts, pathogens and landscape (after Li et al. 2016).

2.3.2.5. Urban land use

The ALLOCATION model of urban development was developed and calibrated for the Hungarian case study. ALLOCATION is a cell-based, integrated model for land-cover change and human population dynamics (see Figure 2.6 for the model framework). In the model, urban land class extents (demands) are first estimated at a regional (NUTS2) level by linear regressive functions of GDP, population and age-structures. The impact of temperature rise on GDP, as a consequence of high-end climate change, is also considered at this stage to reflect climate change impacts on economic development. Projected increases in demand, at a NUTS2-level, are subsequently distributed to 1km^2 cells. The expected cell-level increase of each land class is estimated as a function of: (i) the cell development potential, estimated by a logistic regression model of cell- and NUTS5- level accessibility and landscape configuration; and (ii) policy preferences, which prioritise the development of certain land classes (e.g. commercial centre and industrial park) in particular regions and control the urban developmental form (e.g. compactness versus sprawl).

Within the Hungarian case study, the influence of the following aspects on urban development were considered: economy, climate, demographics, residential preference and urban planning. These impacts were quantified as scenario drivers using different approaches (Figure 2.6) and their consequences for future urban land cover and population distribution patterns projected with the ALLOCATION model.

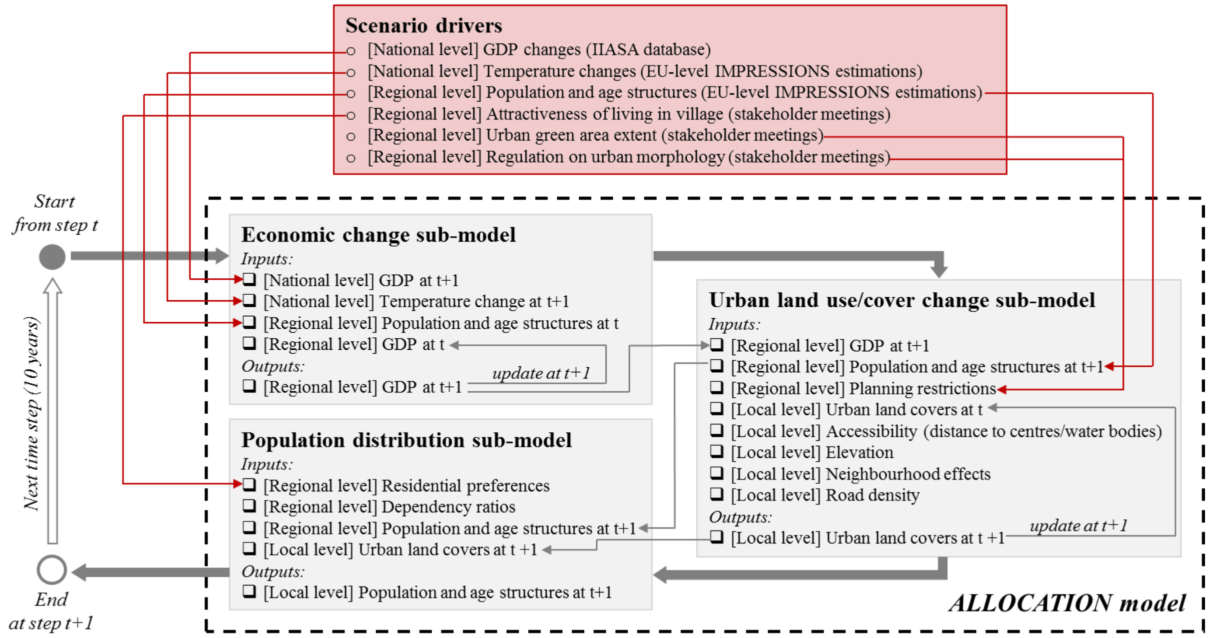


Figure 2.6: ALLOCATION model structure, parameters and scenario drivers.

2.3.3. Agent-based models

2.3.3.1. APORIA

The APORIA framework for agricultural land use change (Murray-Rust et al., 2014) was used in the development of an agent-based model for arable land use change (named Aporia-Lite) in the Hungarian case study. The Aporia-Lite model consists of two types of agents (farmers and parcels) and a regime database (Figure 2.7). A farmer agent represents an individual agricultural land manager of specific socio-economic and attitudinal attributes. Their farms are represented as parcel agents depicted by a set of physical attributes. The regime database represents the local knowledge base of crop rotation plans for farmer selection.

The model provides two major functions for farmer type classification and crop rotation plan (regime) selection. A farmer agent is assigned to an "executive type" (i.e. "business-oriented", "traditional, non-diversified", "traditional, diversified" and "supplementary") based on the socio-economic and physical attributes of the farmer and his/her farm. Then, the farmer agent randomly selects a regime from the regime database, according to the empirical rules identified, from a social survey, for the specified farmer type.

Within the Hungarian case study, the impact of climate and socio-economic changes were considered at two levels (Figure 2.7): (i) at the individual-level they affect income (e.g. subsidy in the agricultural sector), access to social network and attitudes towards (the importance of) the environment; and (ii) at the landscape level they influence crop yield and regional demand for agricultural land.

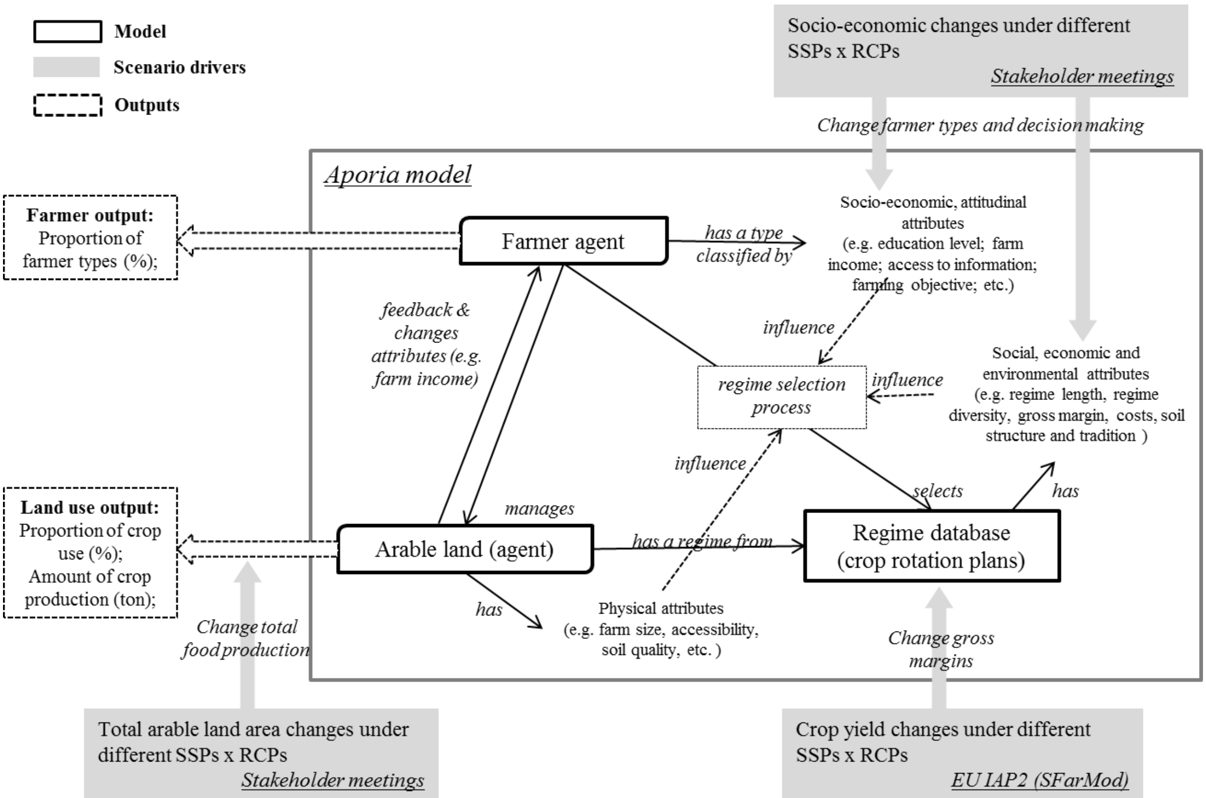


Figure 2.7: The theoretical framework of the Aporia-Lite model and scenario drivers.

2.3.4. Scenario-neutral model applications using impact response surfaces

A subset of the CCIAV models, used within the regional case studies, were included in a sensitivity analysis to assess the influence of changes in key climate and socio-economic variables. In this approach, two (sensitivity) variables were modified to determine their influence on a third (response) variable (Table 2.5). Results were plotted as impact response surfaces (IRS); surfaces which allow the visualisation of the sensitivity of the impact variable to key drivers (Fronzek et al., 2010). This approach has been described as scenario-neutral, as the model analysis is done prior to, or without the use of, climate or socio-economic scenarios (Prudhomme et al., 2010). IRS were estimated for large European sub-regions (Carter et al., 2015) with results representing the case study regions described in this report.

The ForClim, LandClim and SFARMOD models were specifically adapted for the regional/local case studies (see sections 2.3.2.1 and 2.3.1 above). The M-GAEZ, VISIT and AIM/Health models are global scale models, which were used to supplement the regional/local model applications. These models are described in Deliverable D3A.1 (Carter et al., 2016). A brief overview of each model is given here:

- M-GAEZ is a crop productivity model, which is based on the Global Agro-Ecological Zones methodology (GAEZ – Fischer et al., 2002) and was modified as noted in Masutomi et al. (2009). It has the capability of estimating potential crops yield for 14 crops including rice, wheat and maize considering climate factors such as temperature, precipitation, radiation as well as some other environmental factors such as land characteristics and irrigation rate.
- VISIT is (Vegetation Integrative SImulator for Trace gases) is an integrated model for simulating biogeochemical interactions. The model consists of carbon, nitrogen, and water

cycling schemes, which consider mutual interactions (Ito and Inatomi, 2012). Net primary production (NPP), one of the basic ecosystem functions, is obtained as a difference between plant's photosynthesis and respiration.

- AIM/Health is an epidemiological model which estimates excess mortality due to heat stress at the grid cell level based on daily maximum temperature and population density (Honda et al., 2014). Daily excess mortality due to heat stress is defined as the difference between the daily mortality and the daily mortality at the optimal temperature on days whose daily maximum temperature is higher than the optimal temperature.

Table 2.5: CCIAV models for which impact response surfaces are presented in this report.

Model	Sensitivity variables	Response variables	Regions	Aggregation method
M-GAEZ	T x P	Yield of 7 crops	European regions	Average of grid cells
VISIT	T x P	NPP	European regions	Average of grid cells
ForClim v3.3	T x P	Basal area of 5 tree species	European regions	Representative grid cell
LandClim v1.4	T x P	Forest biomass for 3 tree species	Iberia	Site
SFARMOD	T x P x population x tech. development x CO2	Rural land use (4 classes)	European regions	Average of grid cells
AIM/Health	T x population	Heat excess mortality	European regions	Average of grid cells

2.4. Model applications in IMPRESSIONS

Within each case study region, stakeholder engagement enabled the co-creation of: (i) a series of region-specific, future socio-economic scenarios (Deliverable D2.2 - Kok and Pedde, 2016) that were combined with climate scenarios; (ii) a vision for the region in 2100; and (iii) a set of pathways (actions-required) to achieve this vision. The climate and socio-economic scenarios are described in Section 2.2. The visions and pathways for the three regional case studies will be described in detail in Deliverable D4.2 (due October 2017).

The vision for each region is a statement, defined by stakeholders, about the desirable system conditions in 2100, that is, what they want the future to look like. The vision in IMPRESSIONS is presented in two forms: (i) the storyline, that is, a fully developed narrative constructed from stakeholders' elaborations of aspirations and desirable system conditions for the end of the century; and (ii) vision elements, the main themes of the vision. Pathways represent cross-sectoral progressive courses of actions that consist of a mix of strategies that progressively build up from short-term actions to long-term actions into broader system transformations. Pathways are not random collections of actions but purposive courses of actions, meaning that they are goal-oriented seeking to achieve the vision. Pathways define, within the enabling and disabling conditions and actor-related capacities of each climate and socio-economic scenario combination, a set of actions that, if implemented, might support society in achieving the vision.

Three professionally facilitated stakeholder workshops are associated with each of the three regional/local case studies. These workshops focus on: (i) workshop series #1 - the development of the socio-economic scenarios; (ii) workshop series #2 - the development of draft adaptation and mitigations pathways; and (iii) workshop series #3 – the elaboration of the adaptation and mitigation pathways and the development of transformative solutions to high-end climate change. Modelling applications have contributed to this stakeholder engagement process in each case study through:

(i) Workshop series #1 – identification of key model parameters for the stakeholder-led quantification of the socio-economic scenario narratives, followed by subsequent expert-led quantification of remaining model input parameters.

(ii) Workshop series #2 - selected impact and vulnerability modelling results were presented to stakeholders to illustrate the potential consequences of each of the integrated RCP × SSP scenarios. In response to these modelling results, and bearing in mind the vision, the stakeholders identified a range of adaptation, mitigation and transformation actions that they thought would help to achieve the vision within the context of the scenario.

(iii) Workshop series #3 – the actions within the draft adaptation and mitigation pathways were analysed to identify those actions that could be simulated with the CCIAV models. These were applied to the models to evaluate the degree to which they moved each region closer towards their vision under each of the integrated RCP × SSP scenarios. The models were not able to simulate all vision elements, so a combined qualitative and quantitative approach was developed as illustrated in Figure 2.8. This analysis of the effectiveness of the pathways is being used to stimulate stakeholders to add additional actions to the pathways to move closer to achieving the vision. Detailed presentation of this methodology and its associated results per case study will be reported in Deliverable D4.2 (due in October 2017). Some preliminary results are shown in Section 4.3.

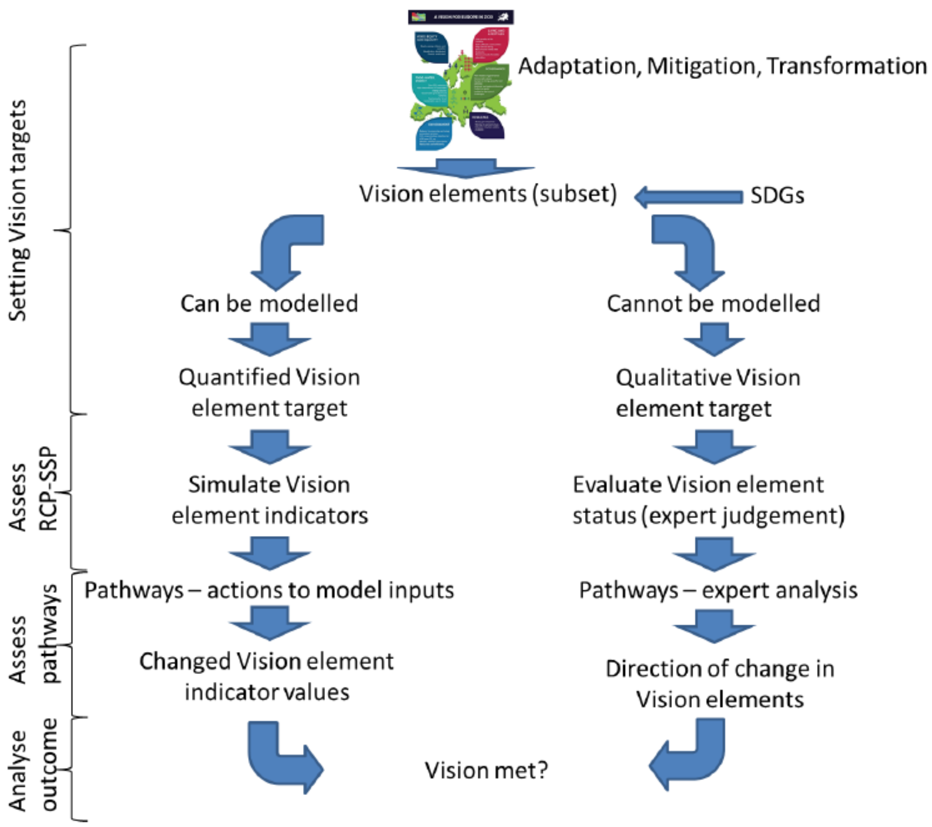


Figure 2.8: An overview of the methodology used to assess pathway effectiveness for each RCP x SSP scenario combination.

3. Future impacts and vulnerability

3.1. Hungary

3.1.1. Climate and socio-economic scenarios

3.1.1.1 *Climate scenarios*

For Hungary, the selected sub-set of climate models project the mean annual temperature to increase by between 2.0 and 5.1°C by 2071-2100. The spread is due to differences in the emission scenarios (RCP4.5 and RCP8.5) as well as differences between projections from different climate models. Most models project the largest temperature increase to occur in summer. The models agree less well on precipitation changes, but most of the selected models agree that mean annual precipitation will increase slightly (by 2 to 10%). Further details of the climate scenarios are given in Deliverable D2.3 (Madsen et al., 2016).

3.1.1.2 *Socio-economic scenarios*

A brief overview of the four socio-economic scenarios for Hungary is described below. Further details are given in Deliverable D2.2 (Kok and Pedde, 2016).

<u>Hungarian SSP1 - Rózsaszin álom</u>

Triggered by changing public opinion on current economic and demographic problems, local governments take the initiative to invest in services. This leads to a local increase in skills and good practices: Veszprém becomes a knowledge centre and Szekszárd turns to sustainable agricultural practices. A new generation of policy-makers come from local communes and represent the will of the people. More transparency and accountability of politicians, reduces corruption. This leads to an economic shift in many sectors, whereby technology development and high-value exports become the new backbone of the Hungarian economy. International cooperation is strong thanks to stable neighbouring countries and decreases in migration. Emigration and birth rates also stabilise. Hungary in 2100 is a fully sustainable, financially healthy and safe country.

<u>Hungarian SSP3 – Regional Rivalry</u>

In the context of increased geopolitical instability and higher energy prices, the Hungarian government shifts its budget away from environmental and social services towards industrial development and defence. However, stalling wages, low resources and unemployment trigger social tensions and a brain drain. The government responds with authoritarian measures, further decreasing social services and implementing fossil-fuel subsidy schemes to keep prices artificially low. Poverty increases and people move out of cities; urban and rural ghettos develop. People try to become self-sufficient by re-learning old practices. By 2100, Hungary is affected by energy shortages; large-scale agricultural and urbanisation are halted. Because of increased migration, a new multicultural society emerges.

<u>Hungarian SSP4 – Inequality</u>

The direction of tender systems strengthens a power system leading to the concentration of power and landownership in the hands of a few. With corruption and tensions on the rise, new elections promise change but fail: new leadership brings stability but strengthens the power of elites. The EU is complacent. A centralised Hungary stabilises borders and supplies a cheap (but low educated) labour force. Health and education services are minimal and the state prefer to manage crises rather than prevent them. The poor (“have-nots”) self-organise to cope with a life which for the majority is still a struggle, with a controlled media and education system. With growing hunger riots, the elites show flexibility to avoid revolts (thawing of dictatorship) with a new charismatic leader. People live in a very unequal world but they are happy with what they have.

Hungarian SSP5 - Pató Pál Ur

Lifestyles in Hungary are increasingly coupled with increased consumption, less social interactions and pervasive technology. Higher energy demand is met with readily available fossil fuels and little investments in new energy or infrastructure. An exclusive development model sets up, with rising corruption. However, popularity is high because of effective crises management and welfare spending. Even if education is stratified, with high mobility for the rich, all layers of society have a decent energy-hungry lifestyle. Technology can fix temporarily the wide spreading environmental and health degradation until the system collapses. The increasing awareness for change leads to a rebirth of communities. Hungary returns on the bumpy path towards a post fossil fuel era that was abandoned decades before.

3.1.2 Model applications for human well-being

3.1.2.1 *Lyme disease risk*

Within the Hungarian case study, Lyme disease risks are projected to increase due to (i) higher temperatures, which increase tick activity, and (ii) a greater extent of forest areas, which represent a major tick habitat. Lyme disease risk is projected to increase in all RCPxSSP scenarios due to the dominant role of increasing temperatures. The SSP3 and SSP5 scenarios are projected to lead to higher (relative) disease risks due to a projected temperature increase of 5.5°C by 2100 (RCP8.5), and projected large (more than 40%) increase in forest areas (Figure 3.1 and 3.2).

In SSP1 × RCP4.5, forests are projected (by the European IAP2) to decrease in part because of: (i) higher forest productivity levels (because of CO_2), and/or (ii) wood demand declines. In the presence of these projected forest declines, Lyme disease risks are, however, still amplified (compared to baseline) as a consequence of the strong effects of temperature increases. Risk is projected to increase nationwide and is greater at higher elevation (northern and western Hungary), where forests are present. Compared to other modelled scenarios, the projected risks in SSP1 are comparatively lower by 2100.

In the other three scenarios (SSP3 × RCP8.5, SSP4 × RCP4.5 and SSP5 × RCP8.5), both temperature and forest area are projected to increase, leading to an increase in disease risk. Within SSP3 and SSP4, unmanaged forests are projected to increase greatly due to declining food demand and/or reduced food production profitability due to climate change (hence agricultural lands are left unmanaged, especially those used for dairying and grazing, and converted to forests). The SSP5 scenario is characterised by a slight increase in managed forest, due to increasing demand for wood products, and, (ii) an increase in unmanaged forests, a consequence of a contraction in the extent of agricultural land (because of improvements in yield and mechanisation). Projected increases in Lyme disease risk, for each of these scenarios, are greater at higher elevations (northern and western Hungary), where forests are present and projected to expand. As the SSP5 × RCP8.5 scenario is projected to have the greatest increase in both temperature and forest area, the increase in disease risk is highest when compared across all of the scenarios.

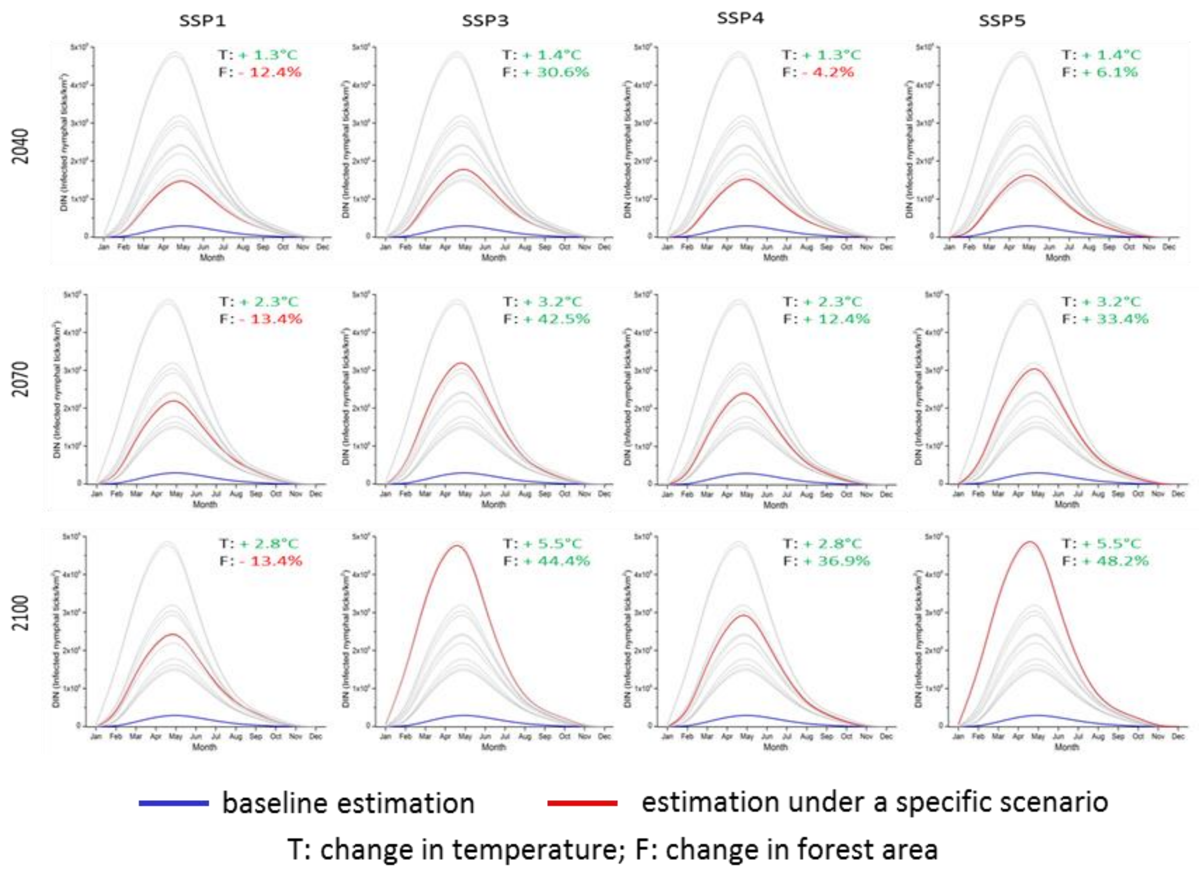


Figure 3.1: Projected seasonal change in DIN (number of infected nymphal ticks per km^2) under the four-modelled RCP × SSP scenario combinations.

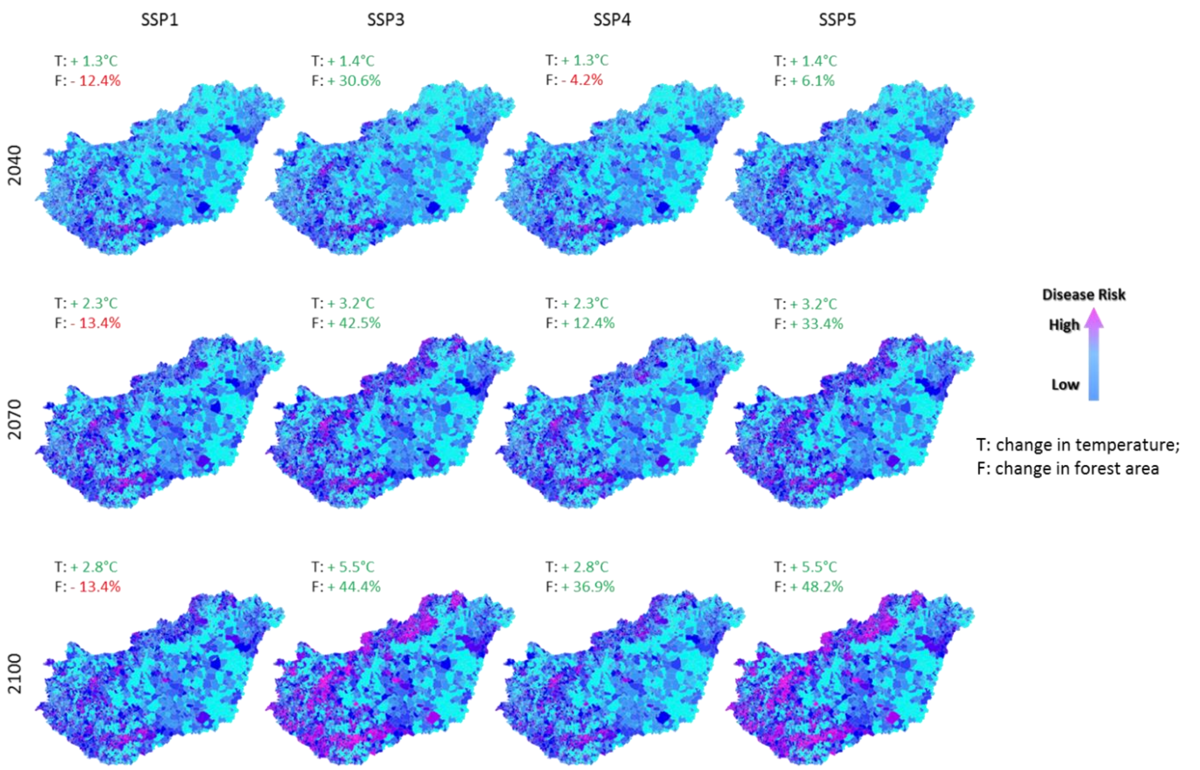


Figure 3.2: Projected change in DIN (number of infected nymphal ticks per km^2) distribution under the four-modelled RCP × SSP scenario combinations.

3.1.2.2. *Heat stress mortality*

Heat waves are an emerging public health problem. Hungary has experienced severe heat waves in 2003, 2007, 2011 and 2012. Epidemiological studies have shown that high temperatures increase daily mortality. The heat stress model quantifies this association between high temperatures (above a threshold value) and daily mortality. This association is then used to estimate the annual burden of heat-related mortality, now and in the future, in Budapest, Szekszárd and Veszprém for two climate futures: RCP4.5 (intermediate) and RCP8.5 (high end).

Heat-related mortality must be placed within the context of the socio-economic scenarios. Projections of the crude death rate for Hungary by SSP demonstrate the contrasting trends projected for each scenario (Figure 3.3). Crude death rates (per 1000 people in the total population) are projected, for example, to increase over time in SSP3 and SSP4. This is in contrast to the declining trend in SSP5. National-scale trends mask regional-scale variability with trends in the crude number of deaths in Budapest, Tolna and Veszprém, by SSP, showing less marked SSP-specific differences, particularly towards the end of the century.

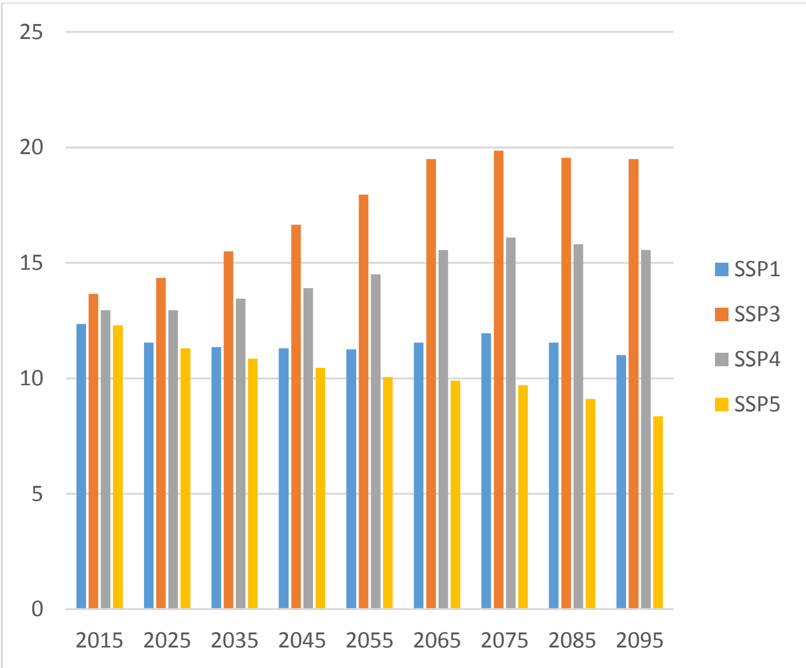


Figure 3.3: Crude death rate in Hungary (per 1000 total population) under each Shared Socioeconomic Pathway (SSP) from 2015 to 2095.

Estimates of the annual number of heat-related deaths for the two communities of Szekszárd and Veszprém are shown in Table 3.1. Heat-related deaths are projected to increase under all scenarios, but most significantly under SSP3 and SSP5, which are associated with more extreme climate changes (RCP8.5). Here, heat-related deaths increase by around 130% in Szekszárd and around 140% in Veszprém by the end of the century. A much lower percentage increase in heat-related deaths are projected for SSPs 1 and 4, which are associated with RCP4.5, of around 22-29% for Szekszárd and 24-31% for Veszprém by the 2080s period (2071-2100).

Table 3.1: Annual number of heat-related deaths estimated for Szekszárd and Veszprém under the four climate and socio-economic scenarios.

Time	SSP1xRCP4.5		SSP3xRCP8.5		SSP4xRCP4.5		SSP5xRCP8.5	
	Szekszárd	Veszprém	Szekszárd	Veszprém	Szekszárd	Veszprém	Szekszárd	Veszprém
Current	171	151	171	151	171	151	171	151
2020S	184	161	203	175	208	183	184	141
2050S	190	159	302	261	219	183	242	209
2080S	208	187	392	362	221	198	396	366

The number of days with heat alerts and heat alarms per decade (currently used as health warnings related to heatwaves) are projected to increase significantly under all scenarios in both communities. Under RCP4.5 (SSP1 and SSP4) heat alerts are projected to increase from 122 currently to 344 by 2071-2100 for Szekszárd and from 61 to 225 for Veszprém, whilst heat alarms increase from 18 to 175 in Szekszárd and from 6 to 82 for Veszprém. Under RCP8.5, much more substantial increases are projected by the end of the century (heat alerts: 842 for Szekszárd and 693 for Veszprém; heat alarms: 945 for Szekszárd and 672 for Veszprém). This means that heatwave warnings are likely to be issued continuously over the summer months in Szekszárd by 2100.

Regional-scale heat-stress modelling was supplemented with a broader-scale sensitivity analysis using the AIM/Health model in which temperature and population were varied. Results were aggregated for the eastern European region including Hungary. Impact response surfaces (Figure 3.4), resulting from this sensitivity analysis, show large increases in heat-related mortality in the region. Death rates were projected to more than double for a warming of 2°C and to increase 10-fold for high-end changes of 9°C or greater (Figure 3.4).

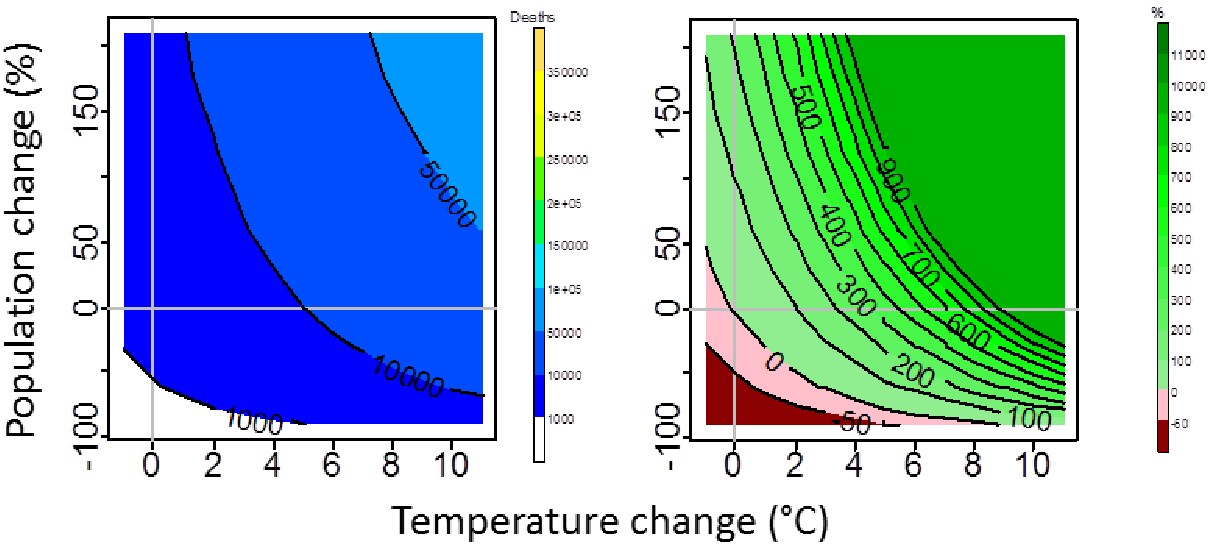


Figure 3.4: Impact response surface for heat-related human mortality averaged for Eastern Europe showing based on the AIM/Health model: (left panel) deaths due to heat events; and (right panel) change relative to current conditions (1981-2010 average temperature and 2010 population).

3.1.3. Model applications for land and water resources

3.1.3.1. *Urban land use change*

Six drivers of urban land use change were selected for quantification and inclusion in the Hungarian case study. Drivers were selected based on data availability, particularly in terms of future scenario projections, the level of interest from local stakeholders and the effort required in their quantification. Selected drivers were quantified and described for each of the integrated climate and socio-economic scenarios (Table 3.2).

Table 3.2: Selected urbanisation drivers and their settings within each of the integrated climate (RCP) and socio-economic (SSP) scenarios.

Scenario driver	Period	Integrated climate and socio-economic scenarios				Estimation method
		SSP1 x RCP4.5	SSP4 x RCP4.5	SSP3 x RCP8.5	SSP5 x RCP8.5	
GDP	2010-2040	+85.10%	+63.74%	+50.63%	+116.91%	IIASA SSP Database
	2040-2070	+40.61%	+15.95%	-2.18%	+94.74%	
	2070-2100	+29.64%	+4.64%	-8.43%	+81.09%	
Temperature	2010-2040	+1.3°C	+1.3°C	+1.4°C	+1.4°C	IMPRESSIONS IAP2
	2040-2070	+1.0°C	+1.0°C	+1.8°C	+1.8°C	
	2070-2100	+0.5°C	+0.5°C	+2.3°C	+2.3°C	
Population	2010-2040	-5.24%	-10.79%	-16.47%	+1.09%	IMPRESSIONS IAP2
	2040-2070	-6.99%	-17.72%	-27.39%	+6.10%	
	2070-2100	-12.21%	-24.82%	-32.71%	+3.54%	
Attractiveness of living in village	2010-2040	-36.33%	-18.33%	0%	-36.33%	Quantification using Fuzzy Set Theory
	2040-2070	0%	-36.33%	+22.17%	-57.67%	
	2070-2100	-36.33%	0%	+22.17%	-36.33%	
Urban green area extent	2010-2040	+11.67%	0%	-8%	-8%	Quantification using Fuzzy Set Theory
	2040-2070	+11.67%	-8%	-8%	-24%	
	2070-2100	+11.67%	-8%	-8%	-24%	
Regulation on urban morphology	2010-2040	compact	compact	sprawl	sprawl+	Qualitative interpretations
	2040-2070	compact	sprawl	sprawl+	sprawl+	
	2070-2100	compact	compact	n/a	sprawl+	

Results show that, despite differences in shape and speed, peri-urbanisation of the Budapest region and out-migration from the centres of the capital/major towns are projected to occur under all scenarios (Figures 3.5 and 3.6). This suggests that future local urban policies should take into consideration the potential under-utilisation of urban infrastructure in the capital centre, and the pressure of social service provisioning in its outskirt.

Under the scenarios combined with intermediate climate change (RCP4.5), urban development paths were projected to be different, as a function of the two socio-economic conditions, describing (i) a sustainable future with less inequality (SSP1), and (ii) an unequal future of increased social, economic and political disparities (SSP4). Under the former integrated scenario (SSP1xRCP4.5), Hungary was projected to have moderate and compact urban growth around the capital and regional centres, accompanied with steady rural out-migration and depopulation. Under the latter scenario (SSP4xRCP4.5), a slow urban growth rate in a compact-sprawl-mixed fashion was projected, with strong national depopulation that is greatest in rural areas.

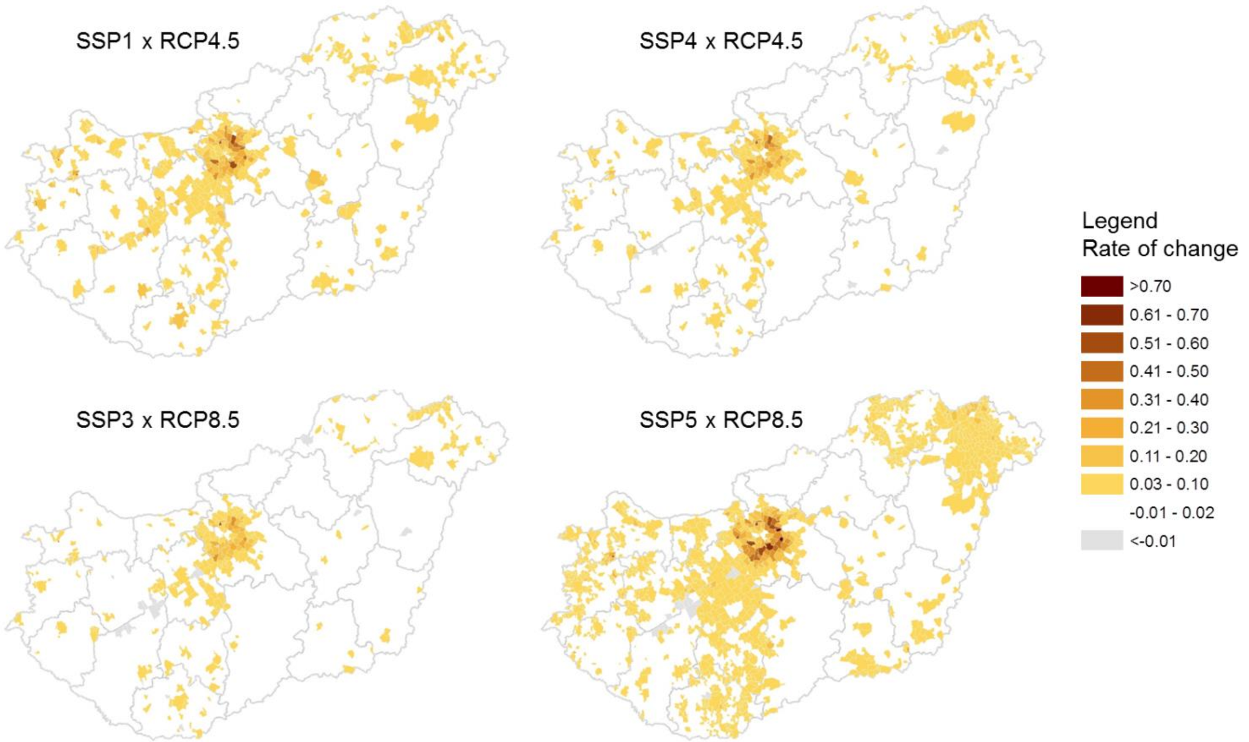


Figure 3.5: Simulated changes in total urban areas from 2010 to 2100 under the four integrated scenarios.

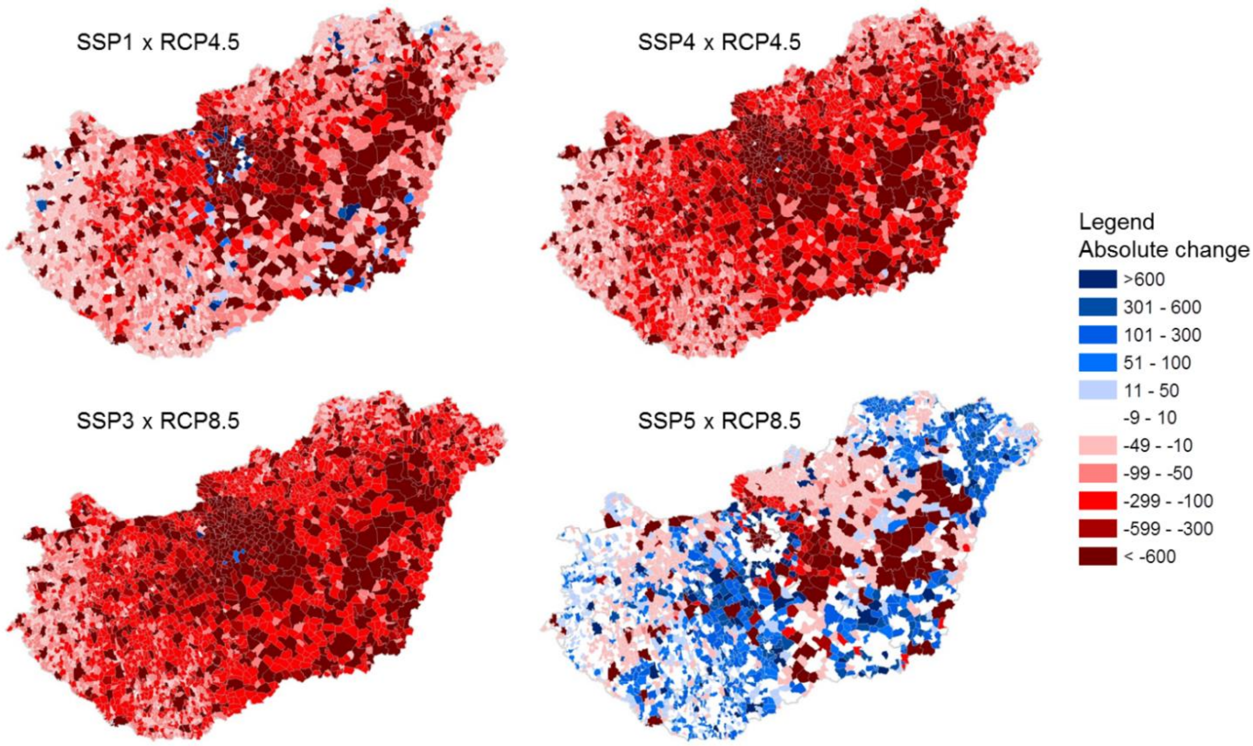


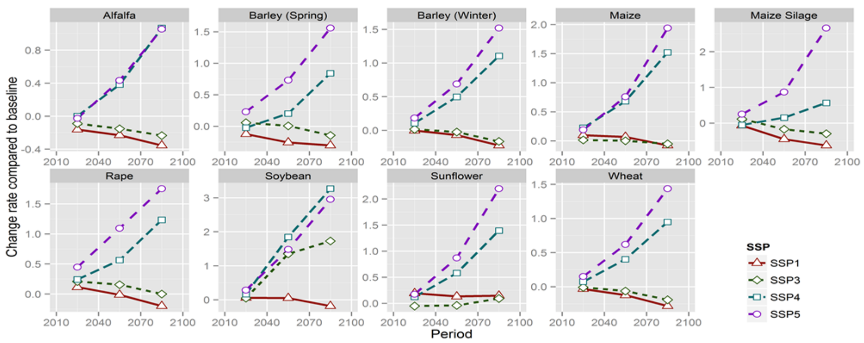
Figure 3.6: Simulated changes from 2010 to 2100 in population density under the four integrated scenarios.

More distinct future urban patterns were projected under the higher-end climate change projections (RCP8.5) and their associated socio-economic scenarios. In a de-globalising future of low-level economic growth and a seriously degraded environment (SSP3), Hungary was projected to have slow and sprawled urban growth across the territory. The capital region was estimated to lose a significant amount of its total population and newly developed residential areas around the capital were likely to be under-utilised. In contrast, in an economically driven future, which is highly industrialised and fossil fuel-based (SSP5), Hungary was projected to have rapid and sprawled urban growth and an overall increase in population. Strong domestic migration was projected to occur in order to occupy the newly developed residential areas. This is likely to result in a more unevenly distributed population pattern.

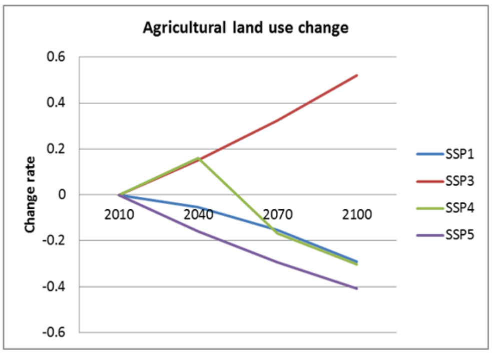
3.1.3.2 *Agricultural land use*

The Aporia-Lite model was used to project changes in agricultural land use for the two Hungarian communities under the four integrated scenarios. Scenario drivers of agricultural land use change within the model were quantified from the stakeholder workshops (change in areal extent of agricultural land area), the European IMPRESSIONS Integrated Assessment Model (IAP2) (crop yields) and the SSP narratives (assumptions on subsidies, social networks and environmental concern) (Figure 3.7).

a) Crop yields of major crops under different scenarios in Hungary predicted by the IAP2



b) Agricultural land cover changes quantified in the stakeholder meeting



c) Socio-economic change assumptions based on the qualitative scenarios from the stakeholder meeting

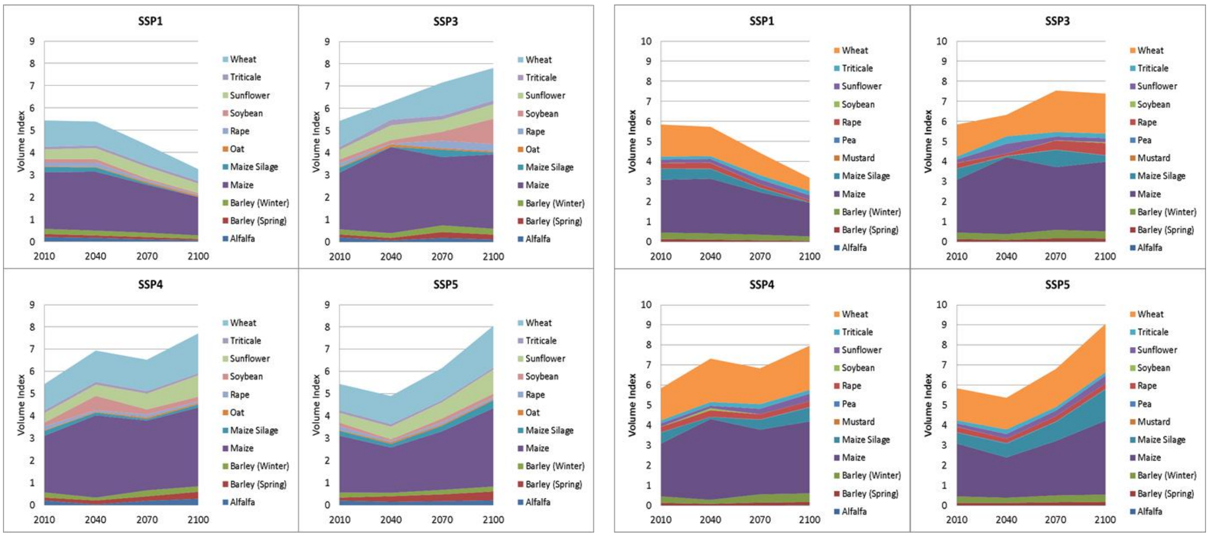
	Time slice	Subsidy	Access to social network	Attitude towards environment
SSP1	2010-2040	+	++	+
SSP1	2040-2070	+	++	+
SSP1	2070-2100	0	++	+
SSP3	2010-2040	0	-	-
SSP3	2040-2070	-	-	-
SSP3	2070-2100	-	-	-
SSP4	2010-2040	-	--	0
SSP4	2040-2070	0	+	+
SSP4	2070-2100	0	0	0
SSP5	2010-2040	0	-	-
SSP5	2040-2070	0	0	0
SSP5	2070-2100	--	+	+

Figure 3.7: Overview of sources and methods used in scenario quantification for agricultural land use modelling.

Future projections in agricultural land use (not shown) reveal differences between the two Hungarian focal areas (Tolna - near Szekszárd - and Veszprém) under the same integrated climate and socio-economic scenario. Under the SSP1 and SSP5 scenarios, despite the projected trends being similar in both areas, the extents of change differed to a certain extent. Conversely, under the SSP3 and SSP4 scenarios, both the trends and extents of change were projected to be distinctly different. These differences projected at the local level are consistent with the national level socio-economic storylines underpinning each scenario, which may imply different levels of challenges for adaptation policies. SSP1 and SSP5 are both associated with rapid economic development, reduced inequality and low challenges to adaptation. In contrast, SSP3 and SSP4 both have slow economic development, increased inequality and high challenges to adaptation to future environmental changes.

Such challenges may further be amplified for Tolna under SSP3 and Veszprém under SSP4. In the former case, a huge decline in major cereals was projected for Tolna, which may threaten the region's capability to be self-sufficient. Moreover, securing food from other regions may be difficult as SSP3 is characterised by various barriers to trade, especially for agricultural products. In the latter case, Veszprém was projected to experience declines in the extent of land under both major cereals and energy crops, but increases in fallow land, which was the highest out of all simulations. This implies that some individual farmers, especially smallholders, may face severe difficulties in sustaining regular food production and thus decide to set their land aside. This situation is likely to be even worse in SSP4, as resources are controlled by the elites, leaving small-scale farmers struggling with low productivity. Fallow lands are thus under risk of abandonment.

Future projections of total crop production (Figure 3.8) are largely determined by the extent of agricultural area (estimated by stakeholders) and crop yield projections (from the European IAP2). In SSP1, both the extent of agricultural area and crop yield are projected to decrease, hence total crop production decreases. In SSP3, the extent of agricultural area is projected to greatly increase but crop yields moderately decrease. As a result, total crop production increases. In SSP4, the extent of agricultural area is projected to moderately decline but crop yield increases greatly, leading to an increase in total crop production. In SSP5, total crop production is projected to increase, as the extent of agricultural area decreases greatly but crop yield increases greatly. The projected ranking of total crop production under different SSPs for Tolna is SSP5 > SSP3 > SSP4 > SSP1, and for Veszprem is SSP5 > SSP4 > SSP3 > SSP1.



Tolna **Veszprem**

Figure 3.8: Projected changes in crop productions for the two case study areas.

In support of regional scale land use modelling, crop yield sensitivity analysis was conducted at a pan-European scale, with the M-GAEZ model, and averaged for the eastern European region, including Hungary. Impact response surfaces show that the model simulates barley and wheat yields to be close to their optimum for baseline conditions. Yields are projected to decrease strongly with decreases in precipitation and for a warming of 4°C or more, increases in precipitation cannot compensate yield decreases due to heat effects (Figure 3.9). Conversely, maize has its temperature optimum above baseline conditions. It should be noted that the fertilising effect of increases in atmospheric CO_2 levels was not accounted for in these sensitivity analysis.

The impact response surface for Net Primary Production (NPP), simulated by the VISIT model, had a shape similar to the crop model impact response surfaces with decreased productivity for drier conditions. The effect of temperature changes on NPP was relatively small (indicated by contour lines largely parallel to the x-axis in Figure 3.9), except for high-end temperature increases above 6°C.

The sensitivity to temperature and precipitation changes of the land use type intensive croplands in eastern Europe, simulated with the SFARMOD model, revealed relatively modest increases for large parts of the impact response surface (Figure 3.9). An exception are decreases in intensive cropland for high-end warming and increases in precipitation.

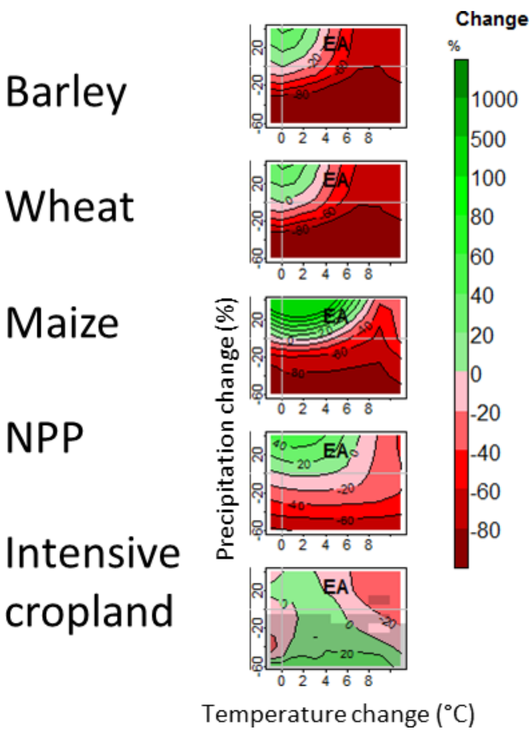


Figure 3.9: Impact response surfaces for changes in crop yields, terrestrial NPP and intensive cropland averaged for eastern Europe relative to the baseline conditions (1981-2010 average climate) for changes in temperature and precipitation. Crop yields were simulated with the M-GAEZ model, NPP with VISIT model and intensive cropland with SFARMOD model.

3.1.3.3. *Water availability*

Initially, the SWIM model was set up for the entire Danube River using the WATCH Era 40 dataset (as described by Stagl and Hattermann, 2015). Within IMPRESSIONS, the model was re-calibrated using the WATCH Era Interim dataset. Since it was not possible to provide discharge data for the case study focal regions, due to scale mismatches (see Section 2.3.2.2), Figure 3.10 provides calibration and validation results at the outlet of the Danube river basin.

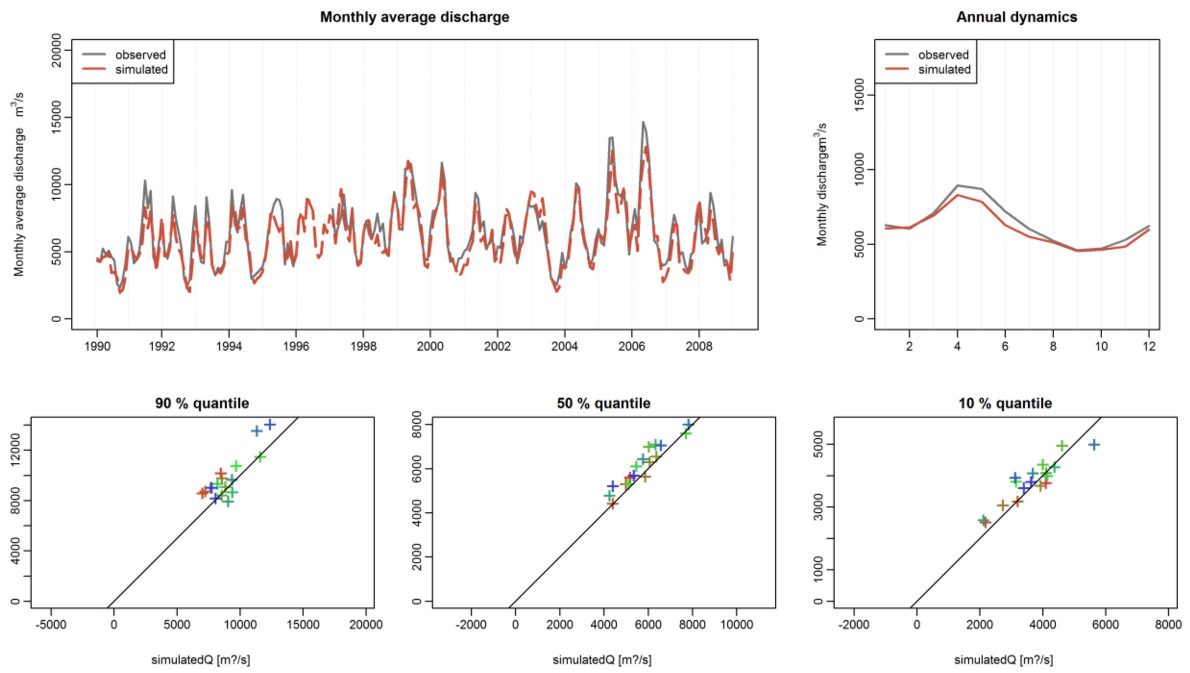


Figure 3.10: Calibration and validation results for monthly discharge at the Danube river outlet (*Ceatal Izmail,* top left), long-term mean annual dynamics (top right), and 90th, 50th and 10th flow percentiles (bottom), driven by the WATCH Era Interim climate.

The Zala is the main tributary of Lake Balaton, covering about 45% of its entire watershed. Projected changes in the flow regime of the Zala are indicative of potential risks to the Lake, which has high economic, ecological and cultural value both for its immediate neighbourhood, including Veszprem and Szekszárd, and for Hungary and central Europe as a whole. However, data from SWIM for Lake Balaton (as presented in Figures 3.11 and 3.12) should be treated as indicative only, as for a full water balance calculation all other inflows and outflows would need to be taken into account.

The discharge of the Zala river is projected to decrease slightly under the RCP4.5 scenario (associated with SSP1 and SSP4), this trend becomes evident by the end of the century, as indicated by the multi-model mean (Figure 3.11). In the case of the RCP8.5 scenario (associated with SSP3 and SSP5), the projected dynamics are similar; however, by the end of the century the multi-model mean projects increase in the discharge (Figure 3.11). This trend should, however, be treated with caution as the strong increase in the discharge is projected by only one (Hadley) model with all the other models projecting discharge decreases.

Figure 3.12 presents deviations in surface runoff relative to the baseline period. Under RCP4.5, annual mean runoff in the area around the Zala river and Lake Balaton decreases slightly by up to -10% until the end of the century. On the other hand, runoff increases slightly in the area next to Veszprém and Szekszárd. Under the RCP8.5 high-end scenario, the area upstream of Lake Balaton is projected to experience slightly reduced runoff in the first time slice and increases in runoff by the end of the century. However, this could be a result of the above mentioned issue of large model spread for this area, where the results of the multi-model mean are biased by the projections from the HadGM model which shows strong increases in the runoff.

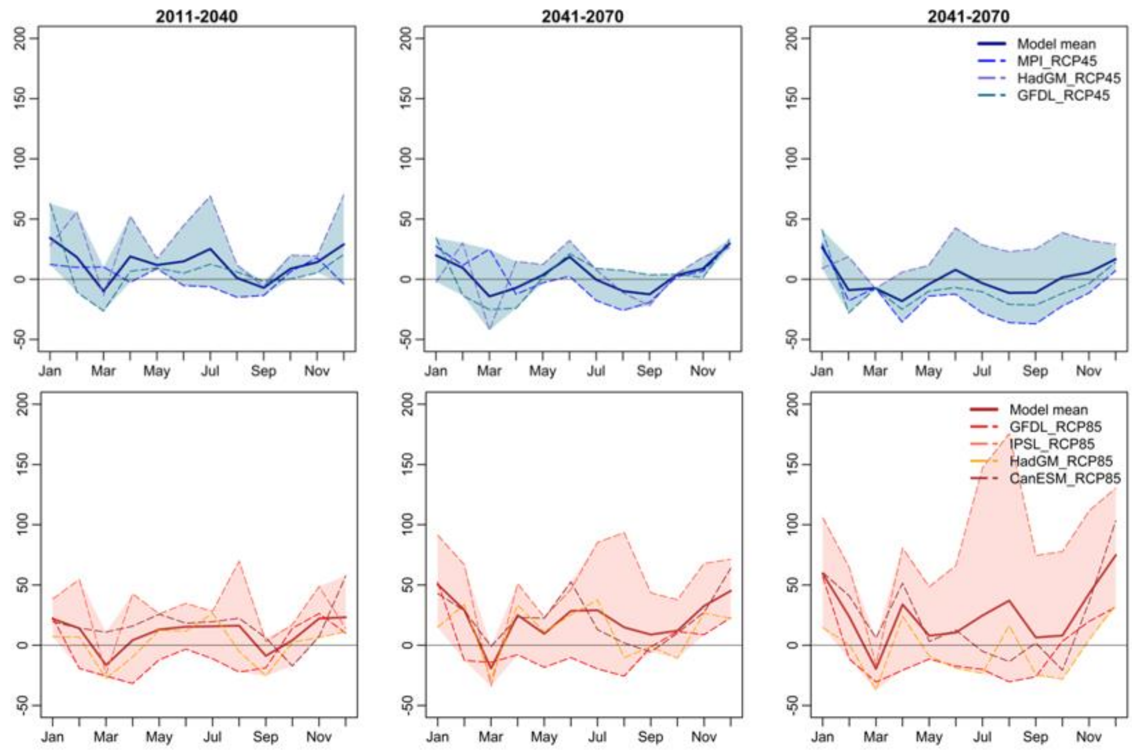


Figure 3.11: Discharge deviation at the Zala river outlet, with respect to the baseline period (1981-2010) for three time slices, for climate projections under RCP4.5 (upper row) and RCP8.5 (lower row) driven by GCM-RCM pairing.

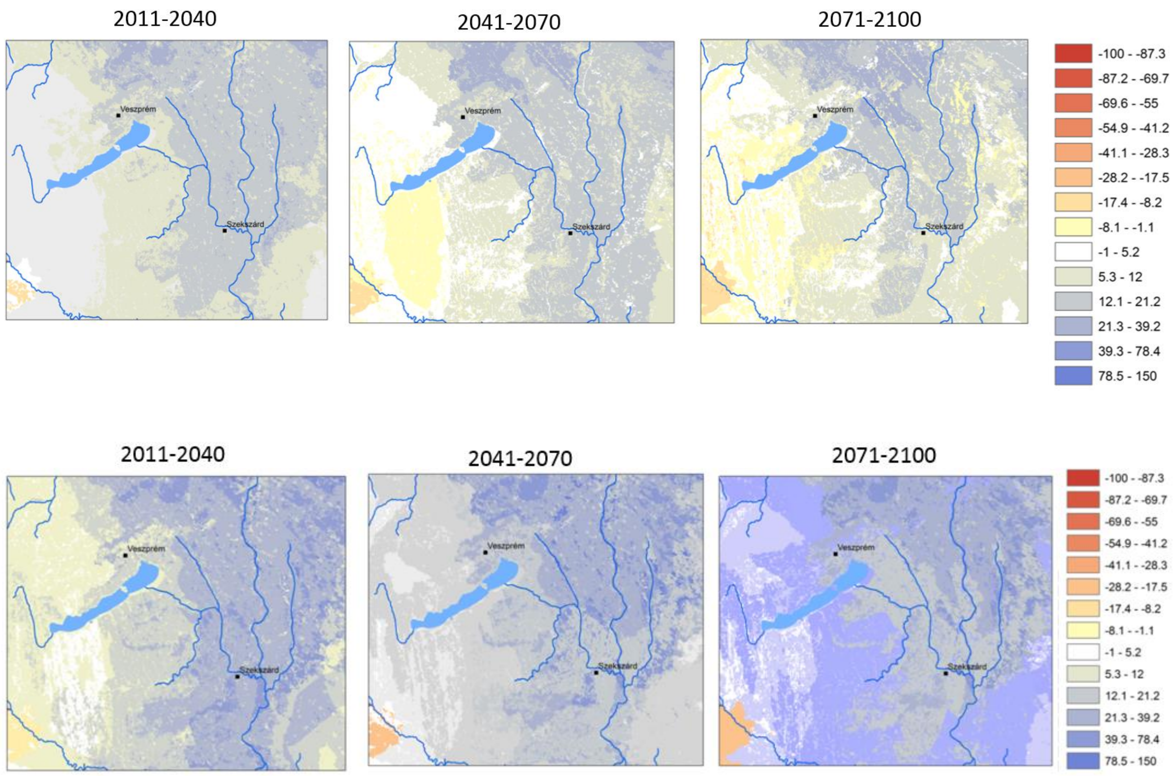


Figure 3.12: Changes in surface runoff at the two case study locations (Veszprém and Szekszárd), under the RCP4.5 (upper 3 maps) and RCP8.5 (lower 3 maps) scenarios for three future periods.

3.1.5 Summary of cross-sectoral issues and vulnerability

The impacts of climate change can already be felt in Hungary: seasons are shifting and extreme weather events are becoming more frequent. Hungary has been experiencing heat waves, extreme droughts and floods, which affect nearly all aspects of life. The main topic areas of the Hungarian case study – agricultural land use, water availability and human health – are all vulnerable to high-end climate change. As described above, extreme heat makes the population vulnerable and leads to increased daily mortality. Although shifts in agricultural land use will be triggered by a series of factors, heat stress also affects agricultural production. The increase in warm days coupled with a lack of fresh water are critical constraints for agriculture. Poor agricultural productivity will ultimately hinder food security. In the same way, water availability is closely intertwined with agricultural production and human health. These cross-sectoral vulnerabilities provide valuable information to decision-makers on the adaptation and mitigation actions that are needed to make Hungary more resilient to high-end climate change.

3.2. Scotland

3.2.1. Climate and socio-economic scenarios

3.2.1.1 *Climate scenarios*

For Scotland, the selected sub-set of climate models project a modest increase in temperature from 0.9 to 3.8°C (1961-1990 vs. 2071-2100) with a relatively small difference between the seasons. The models also agree on a modest increase in annual precipitation and a decrease in precipitation during summer. In addition to these scenarios, a climate analogue approach was also applied for Scotland. This approach made use of one GCM-RCM combination, in this case the EC-Earth global climate model dynamically downscaled with the HIRHAM regional climate model. The projected Scottish temperatures were matched with current climates elsewhere in Europe; i.e. potential European locations with climate characteristics analogous to the projected climate of Scotland under high-end climate change were identified (see section 3.2.2.3). Further information on the climate scenarios is given in Deliverable D2.3 (Madsen et al., 2016).

3.2.1.2. *Socio-economic scenarios*

The four socio-economic scenarios developed with stakeholders for the Scottish case study can be summarised as follows (see Deliverable D2.2 – Kok and Pedde (2016) for further details):

<u>Scottish SSP1 - Mactopia</u>

Through increased societal involvement, policy and effective governance, Scotland achieves the transition towards a sustainable and equitable society by 2040. This transition comes within the context of positive economic development and a further devolution from the UK. Scotland has stronger ties with other like-minded countries both within and outwith the EU. Additional income is generated from the export of surplus water and is invested in social and environmental policies. The shift towards a green (but highly taxed) economy increases tax evasion and resource smuggling. In addition, some social unrest develops as a result of the increase in both unskilled and highly skilled migrants, especially from the rest of the UK. These problems are, however, limited due to high government presence (e.g. with social assimilation programs). By 2070-2100, Scotland has become more aware of national security issues, but the core values of social and environmental sustainability and equity are dominant. Thus, the country remains open to trade by consolidating healthy trade relationships with rich countries, as well as helping with the (economic) development of poor countries. The country has grown a bit less than business-as-usual, but unemployment and homeless people are now something of the past.

Scottish SSP3 - Mad Max

On-going conflicts, political instability and demographic issues in other countries are drivers for increased resource issues and migration to Scotland. Due to increased pressure on resource exploitation, investors buy up land and access to water leading to volatile markets. More and more people have problems buying land, but also food and water. This leads to a society with less solidarity. Energy becomes increasingly valuable and the government sells energy to the highest bidders. These are multinationals who also own large portions of land, control the scarce water and food supplies and determine the consistently high pricing of essential goods and commodities. The fragmentation of society leads to more sectarianism. Conflicts between Catholics and Protestants are rampant, especially in small mining communities in the Highlands. By 2040, the EU breaks down and suffers from social unrest and an economic and energy crisis. In Scotland, a survival from day-to-day, “getting the sandbags out” type of mentality prevails over a long-term structural approach, especially for the poor (“have-nots”). The “haves” on the other hand are preoccupied with securing their fortunes and the few remaining resources. By 2070-2100, a balance is reached where both the “haves” and “have-nots” realise they have to organise themselves: the “haves” to protect themselves and their property; the “have-nots” to survive. These unions originate out of necessity. However, conflict within these groups is also common. There is no, or very limited, contact between the different strata. The poorer Scots work for the richer Scots, but that is the only interaction between them. The whole of society has learned to live with less.

Scottish SSP4 - Tartan Spring

The strong middle class and present prosperity pave the way for technological innovation which leads to a more efficient use of resources. A whole new generation of highly educated young people takes the lead. To capture the full potential of all these technological developments, the Scottish government decides to open resource access to the private sector and to establish liberal market structures. As a result, by 2040 the influence of the private sector in Scotland has become very strong. Economic growth becomes the fundament of Scottish nationalism and political independence is achieved in 2040. The middle class favours further deregulation and cuts in public spending, spearheaded by the economic growth. An unwanted consequence is the disappearance of welfare measures and more public GDP spent on overseas conflicts to secure ownership of access to resources. With more income from resources going to multinationals and little welfare, disparity between the poor and the wealthy in Scotland is more pronounced. This disparity further increases because technological innovation makes it possible to eliminate jobs and manpower. Those that have a job still benefit from privately organised health care schemes, but a large part of the workforce services the super-rich and has only limited social security, barely enough for a decent life. By 2070 people realise that is not enough to live in a rich country which lacks sustainability and accountability of governance. Strikes and uprising become more frequent and violent. Scotland enters turbulent times.

Scottish SSP5 - Techadonia (fossil-fuelled development)

A stabilisation of the fossil fuel price has allowed for an increased tax on fossil fuels. A concomitant increase in immigrants from outside the EU leads the Scottish government to invest extra income in health services, social housing and education. The government also invests in the establishment of for-profit publically owned energy companies, such as Statoil and the Scotland Energy Corporation

(SEC). At the central level, the SEC investment fund has a large stake in fossil fuels and can invest in public services. This means profits stay in Scotland, with SEC paying dividends to each Scottish resident. By 2040, Scottish policy is increasingly driven by technology in many sectors: finance, education (technology university) and labour force. Strong devolution has also resulted in 'clantons'. These become more and more powerful alongside public participation, for example, through an innovative internet referenda. The lack of focus on environmental problems, however, starts to take its toll. Some discontent starts to rise among pockets of the population, driven by issues such as 'the last bumblebee in Scotland'. This is initially partly overshadowed by steady economic growth. By 2070 energy and food demands are met and surpassed. On the other hand, environmental degradation reaches a tipping point. Larger shares of the population realise the high costs of geo-engineering, and the increasing economic inefficiency of fossil fuels. As a result, unhappiness about environmental degradation spreads. After a major clean-up undertaken by SEC, a shift towards renewables triggers a change towards a whole new energy system. SEC investments in renewables slowly increase, matching those in fossil fuels by the end of the century.

3.2.2. Model applications for land use

3.2.2.1. *General trends in land use*

Changes in land use in Scotland were modelled using the IMPRESSIONS integrated assessment model (IAP2) under the four different RCPxSSP scenarios. The IAP2 simulates the responses of eight main land use types to changes in drivers that affect production and/or demand. These land use types are:

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

The modelling of integrated climate (RCP) and socio-economic (SSP) scenarios results in a diversity of land use futures for Scotland (Figure 3.13). This diversity of futures is a consequence of both changing climate and interacting consequences of changing food and timber demand (due to population and GDP change), changing meat demand (due to dietary preferences), changing imports and changes in agricultural productivity associated with different levels of technological innovation.

Important land use trends highlighted by IAP2 land use simulations include:

- **SSP1** - Within SSP1 a greater proportion of Scotland's food is produced locally using sustainable farming practices. Such societal changes would, it is projected, increase the total land area dedicated to both intensive and extensive farming. This changing land use pattern has important implications for forests which rapidly decline.
- **SSP3** – At a national scale, the area of intensive agriculture increases, by a small amount, in Scotland. However, this national scale trend hides spatial differences, with regions of intensive farming expansion and contraction. More substantive changes are projected in grassland (which

shifts towards very extensive production on marginal land) and forest land use types. Within this scenario of food shortage and inequality, unmanaged forest is a potentially important resource for subsistence, small-scale agriculture.

- **SSP4** – Less agricultural land (intensive/extensive) is required within this scenario to meet food demand as a consequence of marginal population increases, increasing food imports and technological improvements. Demand for agricultural land does, however, increase as bioenergy use is projected to increase. Increasing unmanaged forest implies that land is being removed from extensive and intensive agricultural production.
- **SSP5 -** Through the promotion of very intensive, high yielding, technology driven farming, society is able, within this scenario, to produce more food from a smaller area; thus intensive and extensive farming decline in their spatial extent. This declining agricultural area leads to the "freeing-up" of lands and their removal from profit-based food/fibre production; "unmanaged forest" increases. This land could be used for the protection of biodiversity and/or ecosystem service provision. SSP5 is also characterised by the largest increase in urban areas.

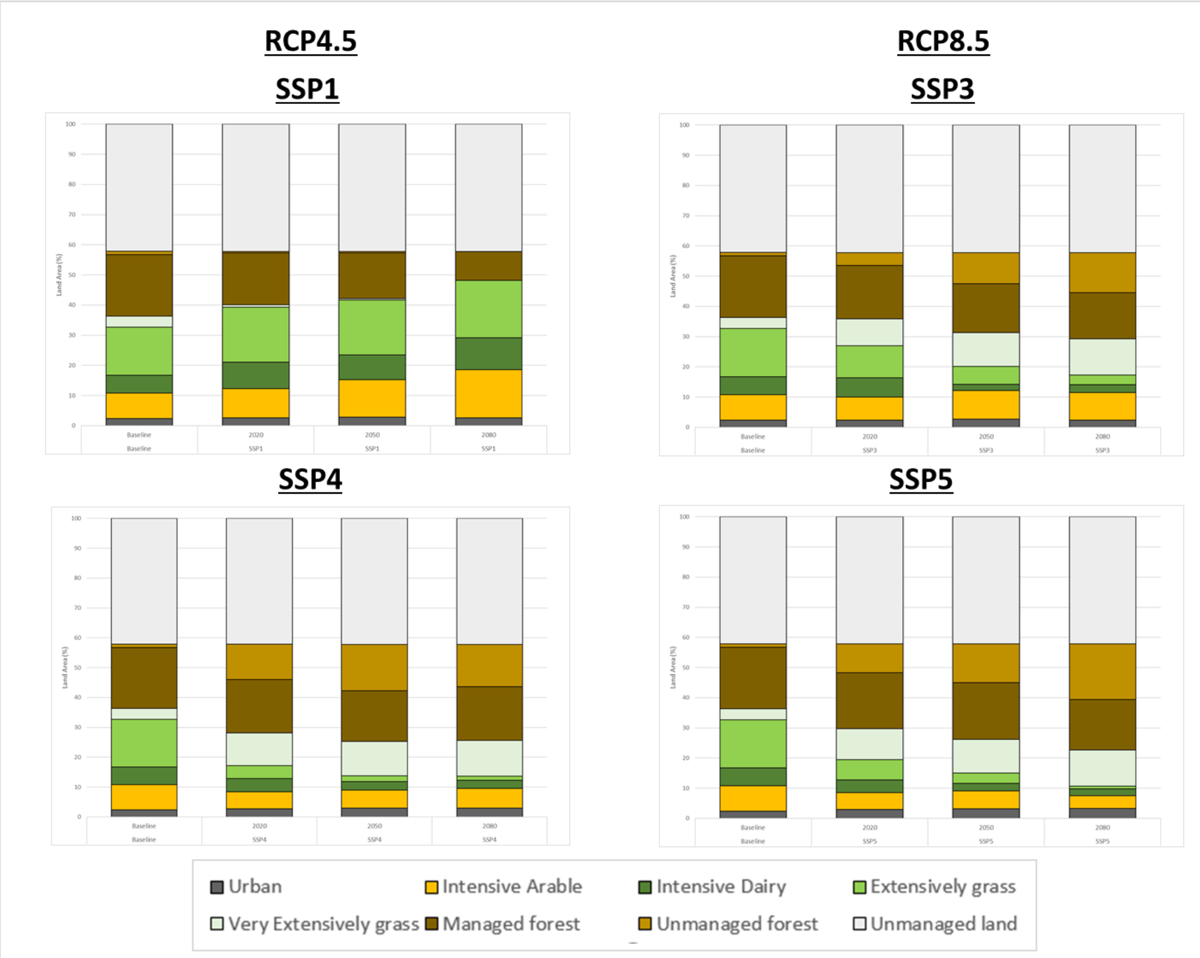


Figure 3.13: Simulated land use within Scotland under a range of climate (RCP) and socio-economic (SSP) scenario combinations using the Scottish IMPRESSIONS IAP2.

3.2.2.2. *Forests*

Increasing the amount of forested land in Scotland is an attractive option for carbon offsetting and as a way to increase timber production, especially since tree growth is currently limited by low temperatures in many parts of Scotland and is thus expected to benefit from climate change. The forest dynamics model ForClim was used to simulate the development of forests stands on a 5 km resolution grid, covering Scotland, and identify locations with the highest potential tree growth and timber production under high-end climate change. Simulations were conducted for multiple climate model (GCM-RCM) combinations for RCP4.5 and RCP8.5.

Managed forests (i.e., even-aged monocultures) were simulated using species that are currently used in Scottish plantations, i.e. Scots pine (*Pinus sylvestris*; endemic) and Sitka spruce (*Picea sitchensis*; exotic), as well as new potential species with a high production potential such as Douglas fir (*Pseudotsuga menziesii*). Management scenarios were species specific. All species were planted at a density of 2500 stems/ha. For Sitka spruce and Douglas fir, two "thinning from below" management actions at an intensity of 30% were simulated after 20 and 30 years. For Scots pine, four "thinning from below" management actions, of an intensity of 20%, were simulated after 30, 40, 50 and 60 years. Rotation lengths were flexible to allow for adaptation to changes in productivity (harvest anticipated in case of increasing productivity, postponed in case of reduced productivity). The timing of the final harvest was defined as a time window in which clear-cut felling was simulated once a species-specific volume threshold had been reached: 70-100 years and volume of 200 m^3/ha for Scots pine, 50-80 years and volume of 300 m^3/ha for Sitka spruce, 40-80 years and volume of 450 m^3/ha for Douglas fir. Results presented here indicate the final volume harvested under baseline climate (upper panel in Figure 3.14) and its projected variation under the high-end scenarios (lower panel, Figure 3.14), when averaging results from RCP4.5 and RCP8.5.

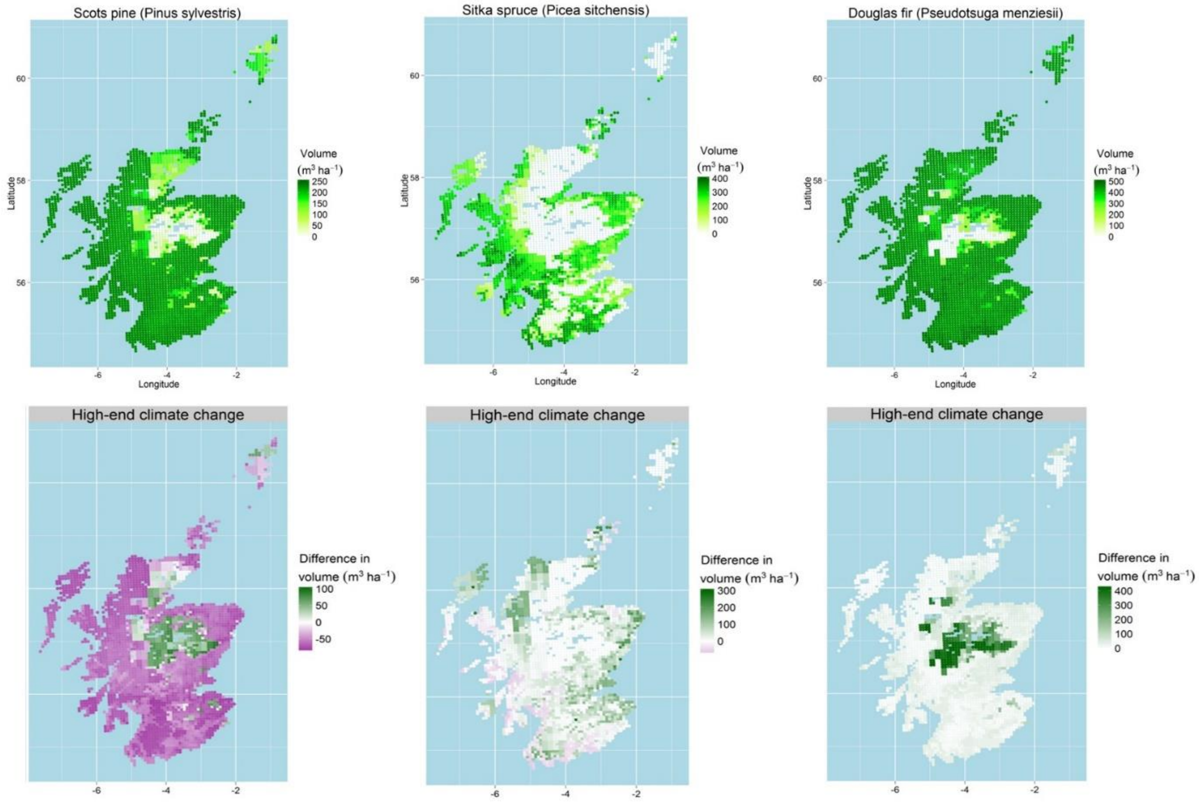


Figure 3.14: Timber production (final volume harvested) predicted under baseline conditions (upper panel) and averaged difference under high-end climate change scenarios (lower panel) for Scots pine (left), Sitka spruce (middle) and Douglas fir (right).

Tree productivity simulated under baseline conditions was consistent with expectations, both in terms of species-specific differences and spatial patterns. Scots pine was the least productive species, Douglas fir the most. Environmental conditions were favourable to tree growth in the Lowlands, a consequence of sufficient soil moisture and a temperate climate. The productivity of Sitka spruce was however, slightly lower than expected and limited to the areas with the most favourable conditions, especially regarding soil moisture (the species is less drought tolerant than the others). Scots pine and Douglas fir both have the potential to reach consistent yields (relative to their potential productivity) almost everywhere with the exclusion of the Highlands. There, and more generally at higher elevations, productivity is currently limited by low temperatures (for Scots pine and Douglas fir) and/or low soil moisture (for Scots pine and Sitka spruce).

The impact of climate change was dependent on the species, location and climate change intensity. By reducing cold limitations, increasing temperatures allowed Scots pine and Douglas fir to establish and grow in the Highlands, but the area remained unsuitable for Sitka spruce. In the Lowlands, the response of the three species was quite different. For Douglas fir, the harvested volumes showed very little variation but the rotation length was shorter (not shown) because of increased productivity, with stronger positive effects for high-end scenarios. For Scots pine, on the contrary, harvested volumes decreased and rotation length increased almost everywhere, but with few differences between climate change scenarios. Sitka spruce's response was more mixed, with both positive (e.g., along the eastern and northwestern coasts) and negative (e.g., in south and southwest) impacts of climate change depending on soil moisture and climate change severity.

Forestry in Scotland might benefit from climate change, especially under scenarios of intermediate climate change severity. Productivity is projected to increase in many areas, and especially in the Highlands, but replacing Scots pine by Sitka spruce or Douglas fir might be necessary to maintain or even increase forest productivity and carbon sequestration. These projections should, however, be interpreted while considering the uncertainty associated with the data, model and modelling choices.

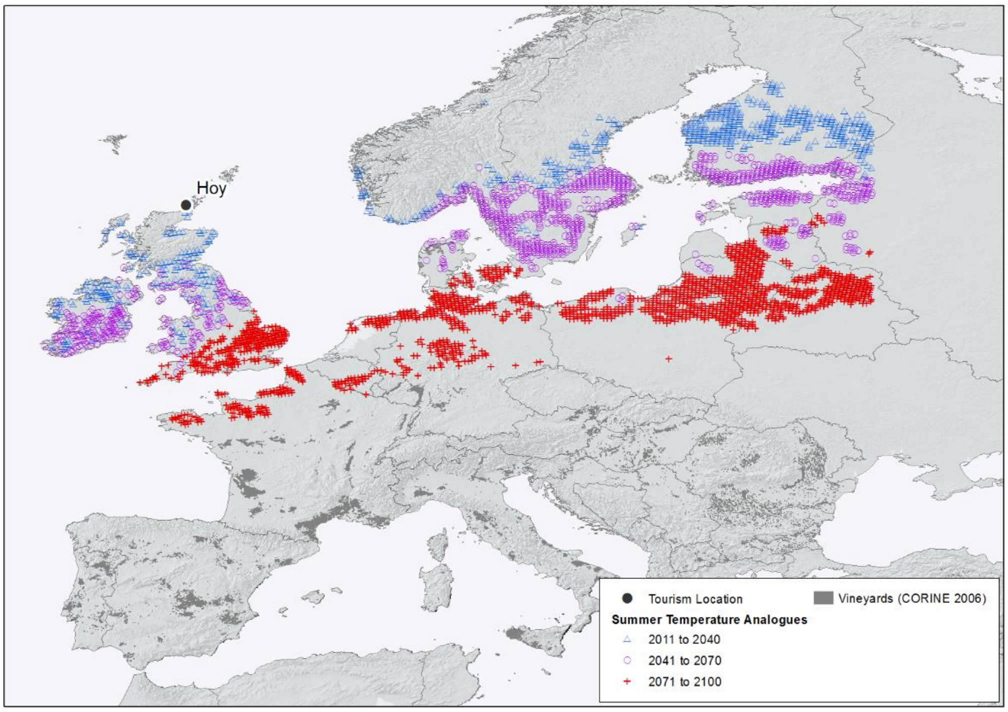
3.2.2.3. *Climate analogues and the wine sector*

Under high-end climate change, temperatures in Scotland are projected to increase significantly by the end of the 21st century. One potential implication for land use in Scotland are changes in growing season temperatures and the associated possibility of producing different agricultural and horticultural crops, including, for example, wine grapes. Wine grapes are grown extensively across central and western Europe, but other than in southern England, are not grown commercially in the UK. This is due primarily to growing season temperatures being lower than required. Under high-end scenarios, growing season temperatures are projected to increase and so, areas at more northerly latitudes may become suitable for wine grape production. As wine production is climate dependent and highly sensitive to weather variability, the sector is a good indicator of ongoing and future climate change impacts.

Climate analogues provide an indication of what the future climate of a given location could be like in comparison to the current climate of another location. Analogues have been generated to visualise the future climate of seven locations within Scotland; locations with diverse climate and landscape features. The locations are: (i) the island of Hoy (in the Orkneys); (ii) Loch Ness; (iii) Glen Coe; (iv) Innerleithen; (v) Quiraing (the Trotternish Ridge on Skye); (vi) the Fife coastal path; and (vii) Loch Etchachan (in the Cairngorms National Park).

Future climate analogues, for summer and annual temperature and precipitation, were derived for these locations from the EC-Earth HadGEM Earth System model (Hazeleger et al., 2012) downscaled to a grid size of 12 x 12 km using the HIRHAM model (Christensen et al., 2006; Lucas-Picher et al., 2013). Comparison of model outputs for climatic variables under RCP8.5 indicated locations within

Europe that currently have the summer and annual climate (temperature and precipitation) characteristics that could be analogous to the climate of Scotland under high-end climate change at the end of the 21st century. As wine grape production is also dependent upon soil type and topography, climate analogues were filtered to identify similarity in lithology (Hartmann and Moosdorf, 2012) and topography. Climate analogues both unfiltered and filtered for lithology/topography are exemplified for the Isle of Hoy (Figure 3.15).



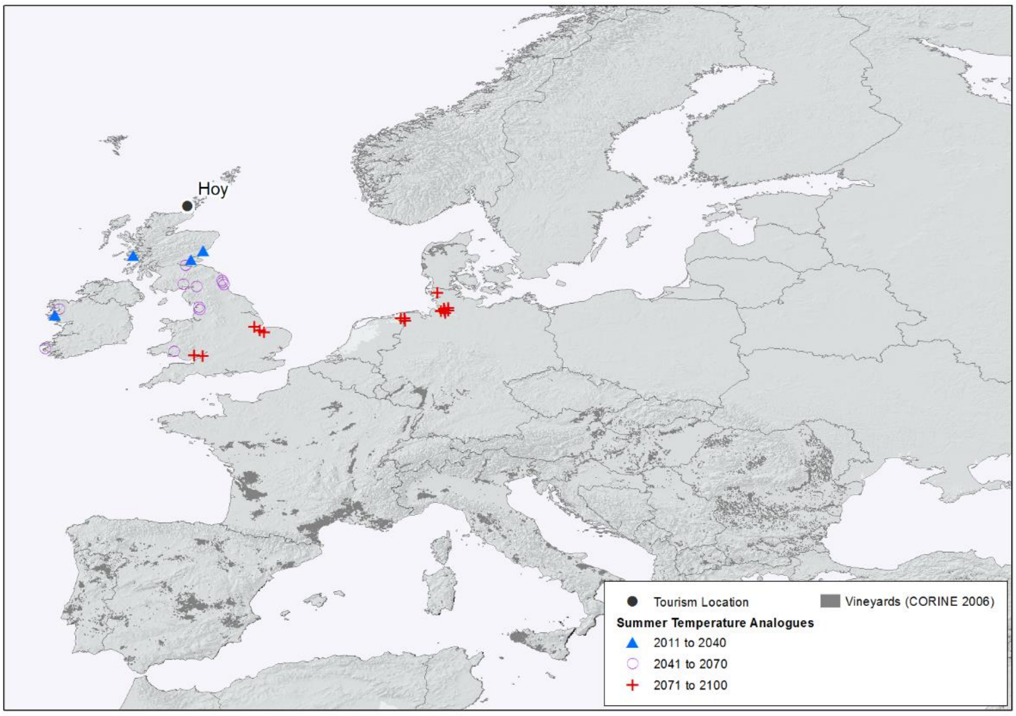


Figure 3.15: Summer temperature analogues for the Isles of Hoy, unfiltered (upper map) and filtered to identify locations with a similar topography and lithology (lower map).

Temperature analogues toward the end of the 21st century occur at more southerly latitudes in Europe, with some variability from west to east arising from the influence of continental climates. Annual temperature analogues were determined to match some current (cool climate) wine producing regions. However, when compared on the basis of summer temperatures, wine production was judged to be marginal (Dunn et al., in review). This is, in part, explained by projected summer temperatures remaining similar to current, that is, relatively cool. Annual temperature projections averages out these important seasonal differences and do not reflect the current strong seasonally divergent (very warm/very cold) climate experienced in many of the climate analogue locations. The further addition of lithology, topography and precipitation considerations was found to largely exclude the potential for wine production in Scotland even under high-end climate change (Dunn et al., in review).

While wine production in Scotland during the next century is unlikely, results have demonstrated that climate analogues are a valuable tool for visualising futures and exploring potential adaptation options. Climate analogues can be contextualised to provide practical, usable information about how people in different land use sectors manage within the context of their climate; lessons that could help to guide those sectors in Scotland with both incremental and transformative adaptation to high-end climate change.

3.2.3. Model applications for human well-being

3.2.3.1. *Lyme Disease*

Lyme disease is the most prevalent vector-borne disease in the temperate Northern Hemisphere; in the UK, the annual number of confirmed Lyme disease cases is over 1000 and still increasing in some areas each year. Changes in Lyme disease risk were simulated on a 1 x 1 km grid for Scotland with a time step of one week using the LYR model (Li et al., 2016). The model was applied to the four integrated climate and socio-economic scenarios.

Under current climate and land use, the predicted Lyme disease risk patterns suggest a spatial endemic foci in the Highlands (e.g., Oban and Inverness) and Tayside (e.g., Perth) and temporal foci in August and September, which are similar to the pattern of human incidence records. The model also projected a general decrease in the density of infected nymphal ticks with increasing altitude in Scotland up to 500m, above which the tick populations were close to zero.

Under the integrated RCPxSSP scenarios, Lyme disease risk is projected to increase in Scotland (Figures 3.16 and 3.17), mainly due to the dominating role of temperature change. SSP3 and SSP5 are projected to have relative higher disease risks, as temperature is projected to increase by 3.5°C by 2100, and there is projected (by the Scottish IAP2) to be a large increase in “extensive agriculture” (grassland) and “unmanaged” (heathland) areas particularly in warmer regions of Scotland. In the model, semi-natural grassland and dwarf shrub heathland are important tick habitats.

The increases in temperature were projected to cause ticks to resume development earlier in spring (Figure 3.16). Thus, the duration of the interstadial development phase was projected to be shortened and a greater tick population was projected to survive before entering into the questing phase. In addition, higher proportions of questing ticks were predicted to become active earlier in the spring and remain active later in the winter, resulting in a prolonged predicted duration of the tick questing season. This could contribute to a greater frequency of tick-host contact and, hence, a greater chance for disease transmission.

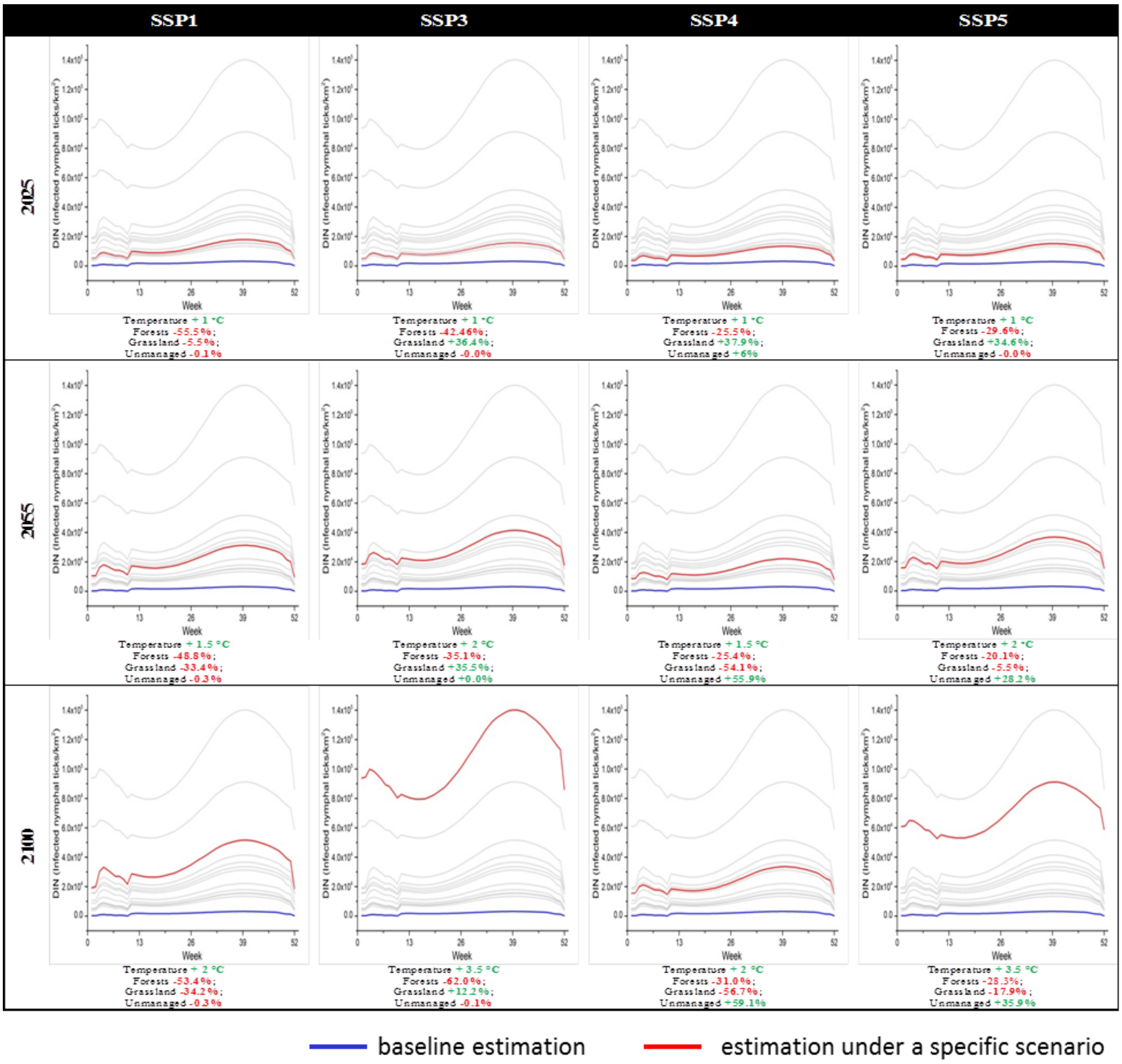


Figure 3.16: Projected seasonal change in DIN (number of infected nymphal ticks per km^2) under different RCPxSSP scenario combinations.

Areas with greater projected increases in disease risk are those at lower altitude, regions where existing tick habitats are largely found and where infected nymphal ticks are already established at a relatively high level (Figure 3.17). The model also projected that high-end climate change could increase the extent of tick infested areas, albeit marginally (less than 4% increase under all scenarios), as the distribution of ticks in mainland Scotland is currently widespread.

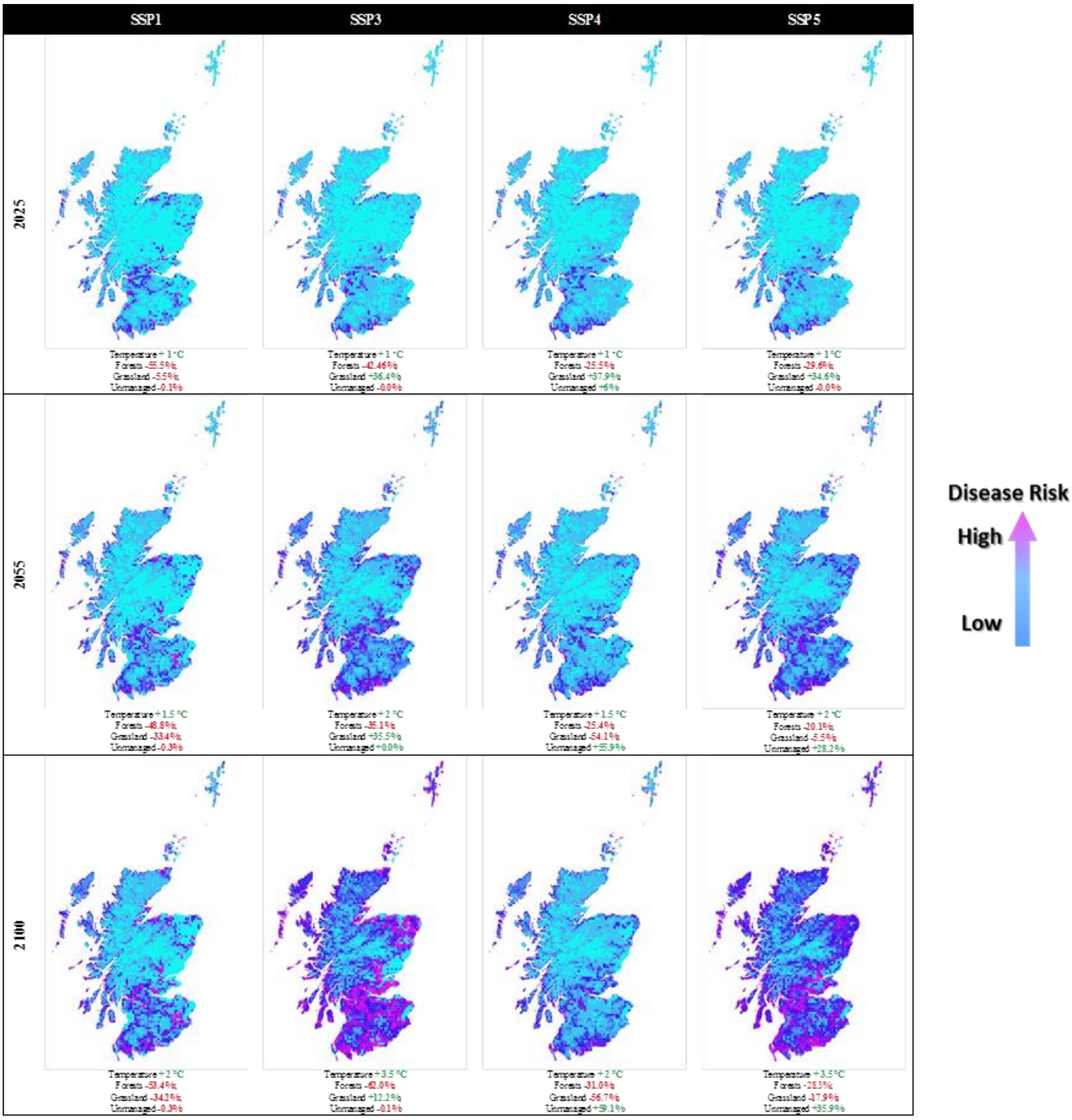


Figure 3.17: Spatial patterns in the projected distribution of peak DIN (number of infected nymphal ticks per km²) in autumn under different RCPxSSP scenario combinations.

3.2.3.2. *Flooding and water availability*

The SWIM model was applied to the Tay river basin to simulate the potential impacts of high-end climate change on Scottish water resources. The following results are presented: (i) simulation results of the SWIM model driven by the WATCH Era Interim (Weedon et al., 2014) dataset for the calibration and validation periods; (ii) deviations (from the baseline period, 1981-2010) in the discharge of the Tay river at the basin outlet (Ballathie gauge), as obtained from the SWIM model simulations driven by the climate projections until the year 2100 under the RCP4.5 and RCP8.5 climate scenarios; and (iii) changes in the number of days exceeding the high flow threshold (Q95 of the baseline period) within the catchment. Changes in discharge at the outlet (Ballathie gauge) were obtained as a percentage of the relative change in the long-term annual average flow for three future periods 2011-2040, 2041-2070 and 2071-2100 with respect to the baseline period 1981-2010.

The SWIM model, when applied to the Tay river basin, did not take into account lakes in the catchment. Some of the natural lakes in the Tay catchment are regulated for the production of hydropower. Data on the operational rules of these hydropower stations was not available. The observed and simulated discharge time series show a good fit, though the model slightly underestimates flows in winter and early spring, and overestimates them in late summer and autumn months (Figure 3.18). High flows were simulated quite well, but the low flows (10th percentile) were systematically underestimated by the model (Figure 3.18).

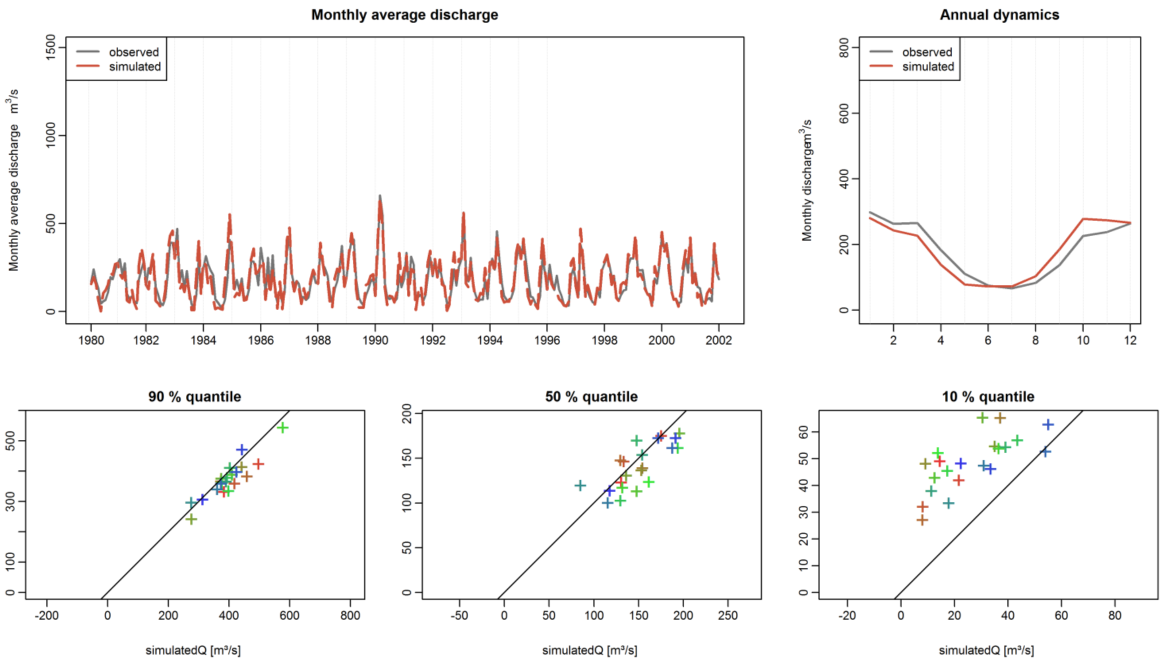


Figure 3.18: Calibration and validation results for the monthly discharge of the Tay river at the outlet, *Ballathie station*, annual long-term average dynamics and 90th, 50th and 10th flow percentiles, simulated with the WATCH Era Interim dataset.

As the SWIM model did not take into account water management within lakes of the Tay river catchment, or any other anthropogenic activities in the river basin, it was not possible to model any of the socio-economic assumptions with respect to changing water management. As a consequence, modelling outcomes consider only changes in climate as projected by RCP4.5 and RCP8.5.

The discharge of the Tay river is projected to increase slightly in the nearest future period (2011–2040), with a maximum of +20% in summer months under both RCPs. In the intermediate (2041–2070) and far (2071–2100) future time slices, the flow is expected to increase in the first half of the year, and slightly decrease in late summer/ early autumn months under both RCPs (Figure 3.19).

The number of days with high flows is also projected to increase. High flow days nearly double under RCP4.5, when compared to the baseline period. A greater increase (more than double the baseline) is observed under RCP8.5 by the end of the century (see Figure 3.20). This potential increase in high flow events could lead to increased flood frequencies in the winter months and decreased river flows in the summer. This could impact upon societal vulnerability to flooding/water-shortages and/or alter the habitats of species putting additional pressure on aquatic ecosystems.

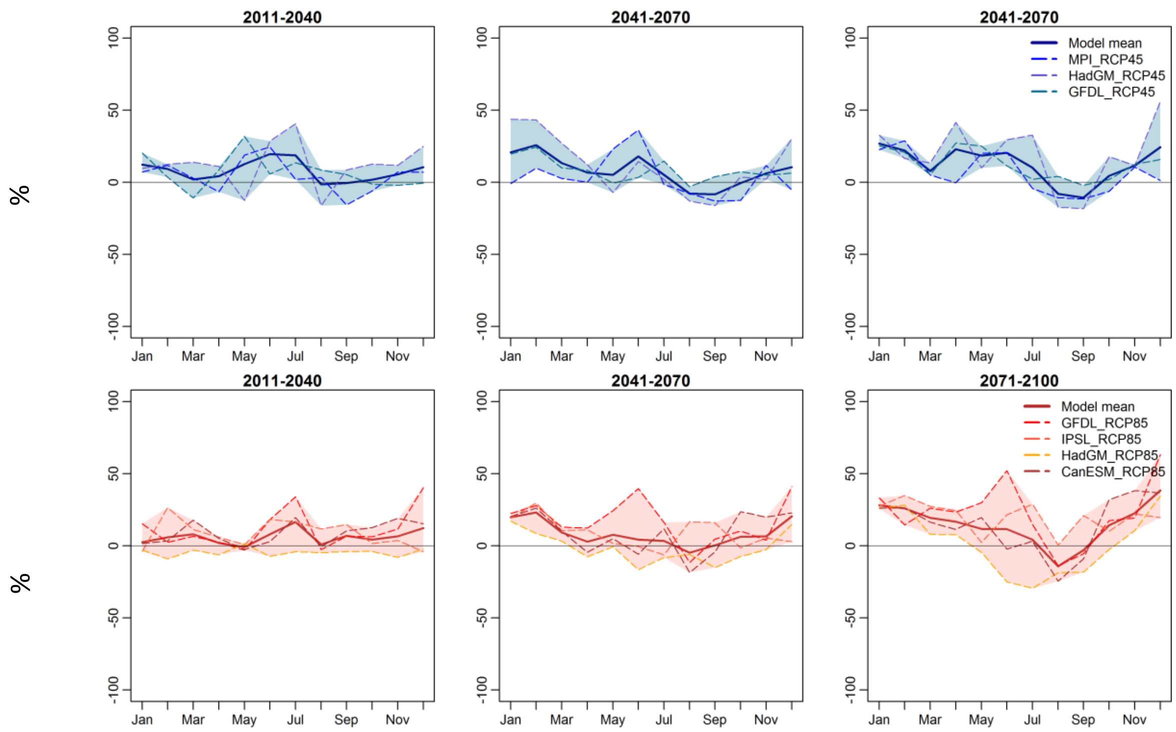


Figure 3.19: Discharge deviation at the Tay river outlet, Ballathie station, with respect to the baseline period for three time slices, for climate projections under RCP4.5 (upper row) and RCP8.5 (lower row) driven by GCM-RCM pairing.

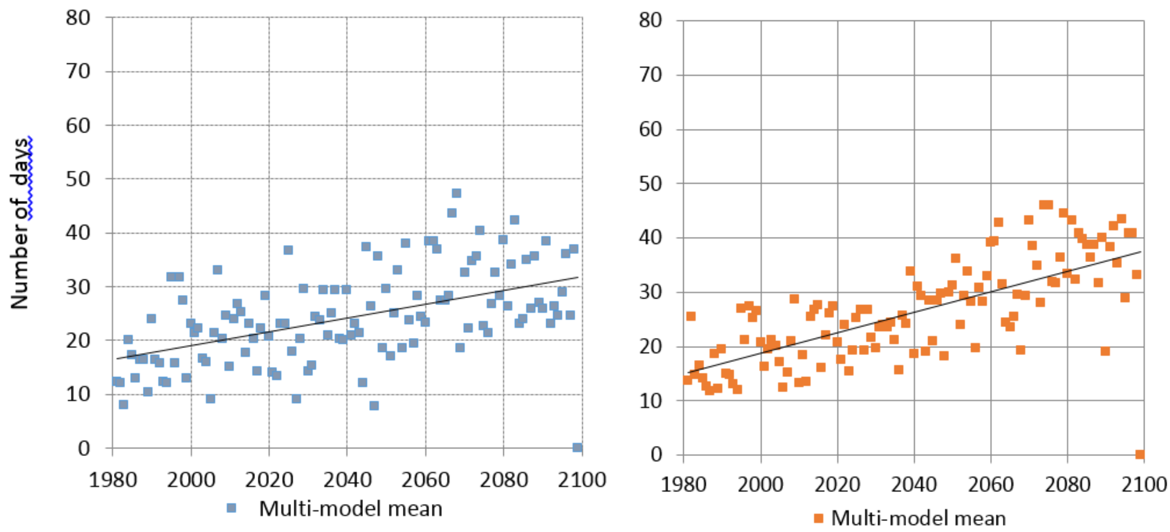


Figure 3.20: The number of high flow events in the period from 1980 to 2100 exceeding the 95th percentile estimated for the baseline period under RCP4.5 (left) and RCP8.5 (right).

3.2.4. Model applications for tourism

The tourism industry is an important contributor to the Scottish economy. A dominant factor motivating summer tourism to Scotland is the Scottish scenery/landscape. However, this landscape is projected to change substantially over the century, influenced both directly and indirectly by climate change. An online questionnaire was used to survey UK nationals (who make up approximately 70%

of summer tourists to Scotland) to explore their stated preferences for photo-based images of visualised landscape changes that may occur under high-end climate change. The focus was on both the participants' personal, subjective aesthetic values of the landscapes and their stated preference for participating in certain activities within the landscapes. Photographs of existing Scottish landscapes were compared with both (i) photo-shopped versions of those landscapes (with a focus on changes to water levels, forest area and vegetation greenness), and (ii) photographs of similar landscapes from climate analogue locations (see section 3.2.2.3).

The questionnaire was designed in three parts. In part one, participants were (independently) shown photos of both the original and analogue landscapes and asked to rate their aesthetic value (on a 5-point Likert scale). Part two used conjoint analysis to compare sets of similar landscape photos, that is, participants were shown sets of two photos (original vs photo-shopped, photo-shopped vs analogue and original vs analogue) and asked to select which photo out of the two they preferred aesthetically. Finally, in part three of the questionnaire, participants were shown photos of each set of three similar landscapes (original, photo-shopped, analogue) and asked whether they preferred one of the versions of that particular landscape over the other two as a location to participate in a particular activity.

Results, from the questionnaire, indicate that the original landscapes are generally preferred, followed by the analogue landscapes, with the photo-shopped landscapes being least appealing. However, no significant aversion to the modified landscapes was identified. The majority of respondents list each landscape as either very attractive or somewhat attractive, with no significant swings in preference between the landscape versions. This finding implies robustness for the Scottish tourism sector, under climate change related landscape changes, as it shows that there is no major aversion to any of the landscape versions.

Differences were apparent between visitors' stated landscape preferences for aesthetics and for participating in activities. For aesthetics, the original version of the landscape is usually preferred. For participating in an activity, preferences change from the original to the analogue versions of the landscapes. For both aesthetic preferences and activity preferences, the photo-shopped versions of the landscapes are generally least preferred. These preferences are likely linked to the lower levels of perceived "naturalness" in the photo-shopped versions of the landscapes.

The stated landscape preferences of the tourism questionnaire were aggregated to explore how changing preferences might influence tourism within a broader geographic region. The Cairngorms National Park (CNP), Scotland's largest national park, was selected as a case study due to the importance of tourism within the regions' economy. Results consistently predicted a decline in visitor trips of approximately -12% and -5% based on the photo-shopped and analogue landscapes, respectively. This decrease is expected to be associated with an overall decline in tourism expenditure, and therefore a potential loss of income from summer tourism. Fluctuations in visitor numbers, as a consequence of future landscape change were, however, shown to be within the inter-annual variability in visitor numbers observed currently for tourism in the CNP. Moreover, the results indicate that the cultural heritage and diversity of landscapes within the CNP have the potential to support a robust tourism industry.

The CNP strategy highlights the variety of landscapes as one of the park's greatest strengths. The results of this analysis demonstrate the importance of managing these differing landscapes to support a robust future tourism industry under high-end climate change. As a precaution, the results suggest that it would be prudent to update existing integrated management plans, such as the CNP strategic plan, to consider the potential influence of landscape change under high-end scenarios on summer visitor numbers in Scotland. This will help to ensure that the park maintains a strong visitor base all year round, and is robust to the direct and indirect impacts of high-end climate change.

3.2.5 Summary of cross-sectoral issues and vulnerability

From the modelling results presented here, it is evident that the landscapes of Scotland will change as a consequence of future climate and socio-economic change. Changing land use patterns and hydrological flows have the potential to influence society's ability to balance food production, biodiversity protection and ecosystem service provision. A changing climate might influence how society manages each of the land sectors and their competing demands. A changing climate could, for example, present opportunities for modified forest species management and/or new agricultural crops (although this is unlikely to include wine production). Changing landscapes influence not only the provisioning services of food, water, fibre but also have the potential to influence the way society interacts with landscapes, as Lyme disease risk increases, and/or perceptions of landscapes change; both key influences on cultural ecosystem services and the Scottish tourism sector.

The Scottish case study has used a range of novel models, methodologies and analytical approaches to explore cross-sectoral impacts and vulnerability. These demonstrate both opportunities and potential risks within the land/water sectors and can aid stakeholders, by informing discussions, in exploring potential mitigation and adaptation pathways.

3.3. Iberia

3.3.1. Climate and socio-economic scenarios

3.3.1.1. *Climate scenarios*

For Iberia, the selected sub-set of climate models show regional warming of between 1.9 and 5.5°C by 2071-2100. Seasonal differences are large; most climate models project the largest warming to occur in summer, but there is a large difference in the signal projected by different models. Projected changes in precipitation are large as well and the selected climate models all project a decrease in annual precipitation. Again, models do not agree on the strength of the signal and the seasonal variations. However, most models project decreases in precipitation in all seasons, with the largest decrease occurring in summer/autumn. Further information on the climate scenarios is given in Deliverable D2.3 (Madsen et al., 2016).

3.3.1.2. *Socio-economic scenarios*

The four socio-economic scenarios developed with stakeholders for the Iberian case study can be summarised as follows (see Deliverable D2.2 – Kok and Pedde (2016) for further details):

<u>Iberia SSP1 - Sustainability</u>

Triggered by continuing and growing social participation in environmental, social and economic issues and fuelled by a European social-oriented political framework, Iberia embraces a path towards a new development model. Initially at a slow pace, but increasing rapidly and supported by socially and environmentally sustainable policy-making, a fundamental change is achieved towards boosting education, innovation, job opportunities in the green sectors (renewables and reuse of materials), and eventually green technologies. Because of the strengthening of the democratic governance structures, globalisation is no longer opposed to local sustainability, rather on the contrary, positive sustainable development synergies are created. This leads to an economic shift in many sectors, whereby technology development and high-value exports become the new backbone of the Iberian economy. By 2100, the new decision-making culture and practice culminates in the new development model for the Iberian countries. This model encourages broad public participation, institutional collaboration and includes a harmonious integration of health, social, economic, political and environmental sectors.

Iberia SSP3 - Regional Rivalry

Short-lived governments lead to a fragmentation of the social and economic fabric in Iberia. In 2030 Catalonia gains independence, which is later followed by other regions both in Iberia and in other Mediterranean countries. To counteract economic crises, the Southern countries unite in a separate Union, the ‘Club Med’. Continued environmental and economic problems increase social tensions and social inequalities, which in turn negatively affect tourism. By the 2060s four countries have come to exist in Iberia: Portugal, Spain, Catalonia and the Basque Country, with strong borders between them. Over time, conflicts escalate although war over water and other scarce resources is prevented. By 2100, a deserted and desertified inland rural Iberia remains and this produces a large divide, even further than with the rest of Europe. Continuous conflicts across multiple countries, which experience similar disintegration processes, occur elsewhere limiting cooperation within Club Med and with other international power blocs.

Iberia SSP4 - Inequality

Economic challenges and environmental accidents are exacerbated by new European and global crises. This, in turn, leads to increased migration from northern Africa and the Middle East. In Iberia, unemployment rises to record levels, this eventually results in social unrest and massive protests. Social stratification intensifies with strong high-income elites and a divided large lower class, bringing about strong tensions within and between social classes. This unstable social situation escalates in the 2040s, and leads to a shift in the political system. New governments establish an oligarchical system with power and money gradually centralised and controlled by an elite of a few companies and central governments. The political and industrial elite successfully implements a strategy of “subtle” enforcement of inequality through education and keeping people busy on low skilled tasks, with low future expectations. To their benefit, the elite invests in solar and wind energy, eventually becoming a market leader.

Iberia SSP5 - Fossil-fuelled Development

The burst of the financial bubble increases the need for social aid and subsidies for Iberia, which is facilitated by an increasing economic surplus in the north of Europe. Crucial is the establishment of a connection of electricity networks that increase access to external (fossil) resources. Iberia is part of this network and located strategically in the energy nexus. Iberia also starts exploiting its own resources, while intensifying agriculture and forestry. In the 2040s, environmental problems occur that are addressed with successful technological solutions. The accompanying environmental destruction goes by unnoticed as most people live in the cities, where water, food, and energy supplies are secured. By 2060, Iberia totally depends on technology, fossil fuels, and investments from large companies. Ultimately, a number of environmental disasters lead to an increased awareness across Iberia that technology can no longer sustain agricultural production. The outlook is uncertain as the fossil-fuel based development model collapses and business opportunities decrease.

3.3.2 Model applications for water resources

The SWIM model was applied to the entire Tagus river basin for all four integrated climate and socio-economic scenarios. The assumptions introduced into the management of water infrastructure to reflect each scenario narrative in the modelling are presented in Table 3.3.

Table 3.3: Modelling assumptions introduced into the management of water infrastructure, within the Tagus river basin, to reflect SSP scenario narratives.

	RCP4.5×SSP1	**RCP4.5×SSP4**	**RCP8.5×SSP3**	**RCP8.5×SSP5**
Importance of Tagus-Segura water Transfer over environmental flows in Tagus headwaters (resembling natural conditions)	Secondary importance	Primary importance (but more water left in the reach to satisfy basic requirements of stakeholders at the Aranjuez. Slightly higher flows are also provided for irrigation in the Tagus itself, still keeping water supply to Segura as the priority)	Primary importance (only the lowest possible discharges are provided at the Aranjuez town)	Primary importance (the demands of the downstream beneficiaries are satisfied to the minimum, discharges are set to the overall minimum, and maximum water is sent to the Segura Basin)
Withdrawals for irrigation and urban water transfer	Decreased (and efficiencies increased, by 40% with respect to 2001-2010)	Increased (especially supply to the Madrid area)	Increased	Strongly increased (especially supply to the Madrid area; however efficiencies also increased due to technological advancement)
Reservoir management	Buendía and Entrepeñas reservoirs management is switched to serve environmental needs of the river	Another large water transfer is organized, from the Valdecanyas reservoir upstream of the Alcantara dam (to satisfy growing needs in the south and lessen stress on headwaters of Tagus)		Another large water transfer is organised, from the Valdecanyas reservoir upstream of the Alcantara dam (to satisfy growing need due to intensive agriculture in the south)
Alcantara dam	Managed as now (implicitly taking into account the Albufeira agreement[2])	Managed as now (implicitly taking into account the Albufeira agreement)	Managed to store more water on the Spanish side, triggering potential conflict with Portugal; after 2040; the dam is managed in the usual way	Operated in the usual way

[2] The Albufeira agreement regulates the water volumes to be discharged at the Cedillo Dam (just downstream of the Alcantara Dam). The volume of water to be discharged yearly according to the Albufeira agreement should not be less than 2700 hm^3 (there are also monthly and weekly thresholds). It is important to note that this thresholds is set for a "normal" year. If there is a drought the threshold is reduced.

Validation statistics show that the model was able to represent the dynamics of discharges from the Tagus river, and the simulated mean monthly discharge shows a reasonably good fit to the observed values (Figure 3.21). However, the low flows, or 10th percentile, show quite a weak comparison with the observed values (Figure 3.21). This weak correlation may be due to the management of the reservoirs (not all of which were included in the SWIM model), as well as the large water withdrawals for irrigation which take place in the summer months

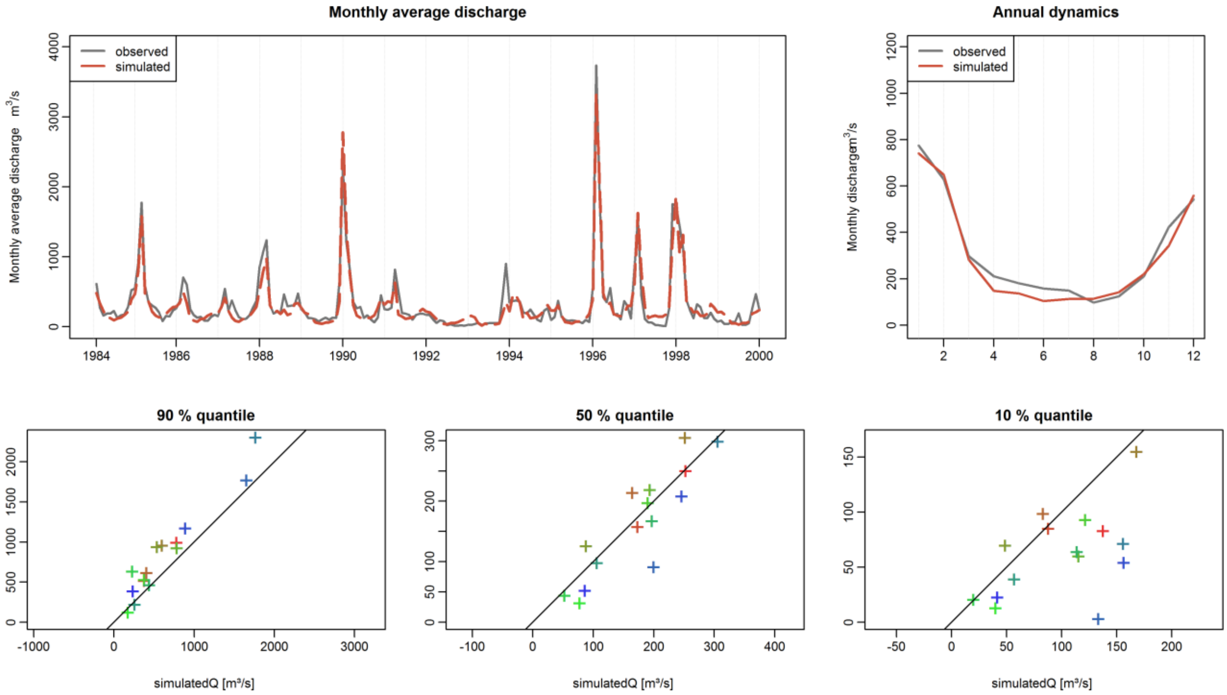


Figure 3.21: Calibration and Validation results for the monthly discharge of the Tagus River outlet, *Almourol station*, annual long-term average dynamics and 90th, 50th and 10th flow percentiles, simulated with WATCH Era Interim.

3.3.2.1. *Water availability*

Decreases in overall water availability are projected under all scenarios by 2071–2100 (Figure 3.22). However, in SSP1xRCP4.5, due to advances in the efficiency of water withdrawals and more efficient water use during the irrigational period (late spring, summer and early autumn), the projected decreases are largely limited for both the 2021–2070 and 2071–2100 time slices. In contrast, discharges at the Tagus river outlet decrease throughout the year in SSP4xRCP4.5 and in both RCP8.5 scenarios (SSP3 and SSP5) across time slices, as a result of climate change impacts and increased water withdrawals.

There are seasonal declines during late autumn and winter in the period 2011–2040 for SSP4xRCP4.5 and SSP3xRCP8.5. Declines in discharge are most severe, however, in SSP3xRCP8.5, with projected decreases of up to 45% and 55%, and SSP5xRCP8.5, with projected decreases of up to 55% and 65%, for the second (2041–2070) and third (2071–2100) time slices, respectively (Figure 3.22). These large declines under RCP8.5 are triggered by increased water withdrawals and the severe impacts of high-end climate change on water availability in the catchment.

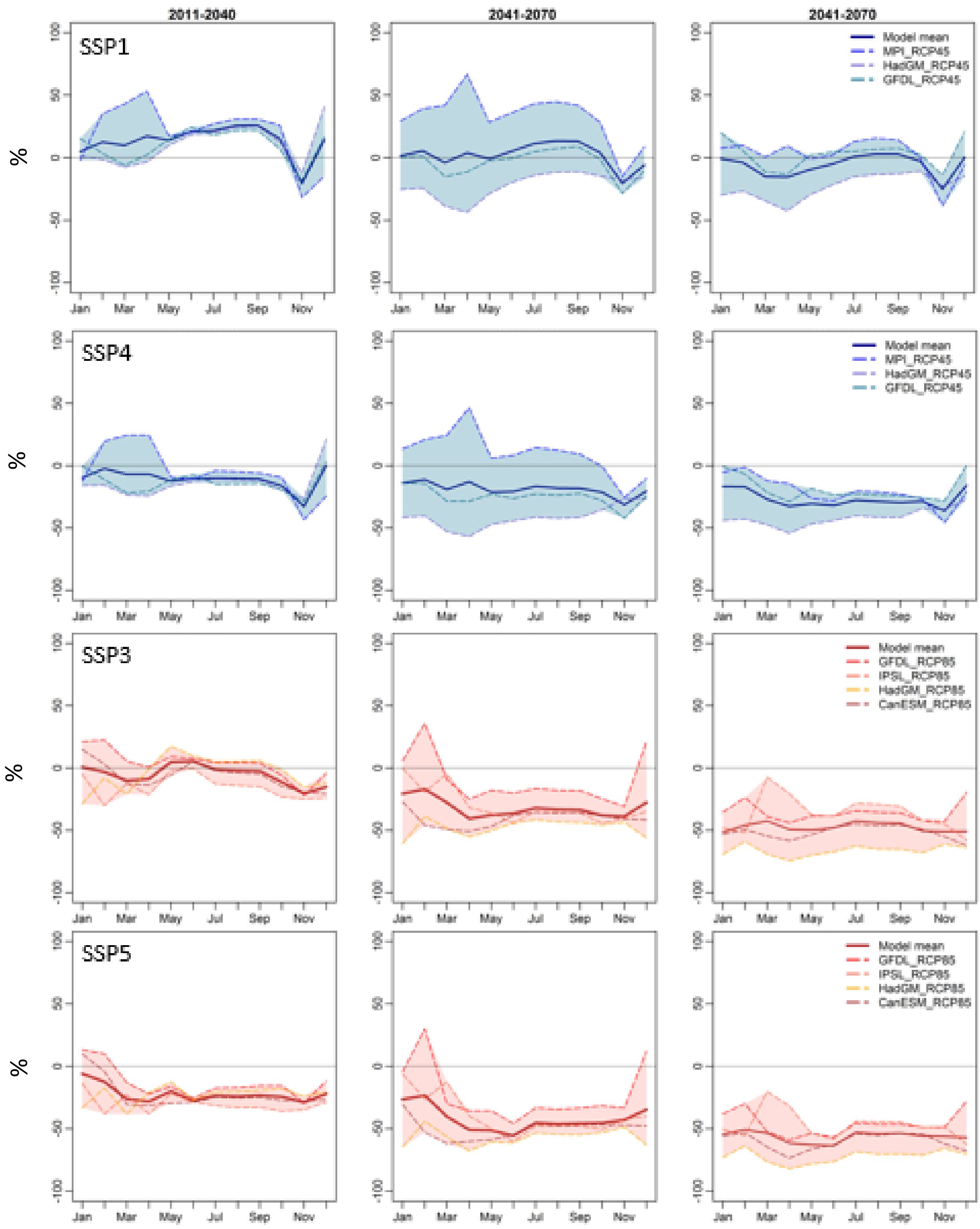


Figure 3.22: Discharge deviation at the outlet of the Tagus river basin under the SSP1xRCP4.5 (first row), SSP4xRCP4.5 (second row), SSP3xRCP8.5 (third row) and SSP5xRCP8.5 (fourth row) scenarios, for three time slices 2011-2040 (left column), 2041-2070 (middle column), 2071-2100 (right column) relative to the baseline period 1981-2010.

In SSP1xRCP4.5, limits to the Tagus-Segura Transfer and the management of the *Buendía* and *Entrepeñas* reservoirs contribute to sustaining real environmental flows in the Tagus river after the withdrawal point to Segura and ensuring reservoir volumes are maintained (Figure 3.23). That is, there is greater discharge in winter and less in summer resembling natural conditions (according to the IHA method of Richter and Baumgartner, 1997). However, the total water volume supplied to Segura (average across models) for the 2011–2040, 2040–2070 and 2070–2100 time slices is 169 hm^3, 155 hm^3 and 117 hm^3, respectively, compared with 350 hm^3 average demand specified in the Segura Basin Management Plan. The volumes supplied to the Segura are lower still under SSP3xRCP8.5 (310 hm^3, 147 hm^3, 101 hm^3) and SSP5xRCP8.5 (149 hm^3, 114 hm^3, 84 hm^3) due to decreased water availability. This indicates that even with demand-oriented management of the infrastructure, decreased water availability leads to a failure to meet the water demand goals of the south.

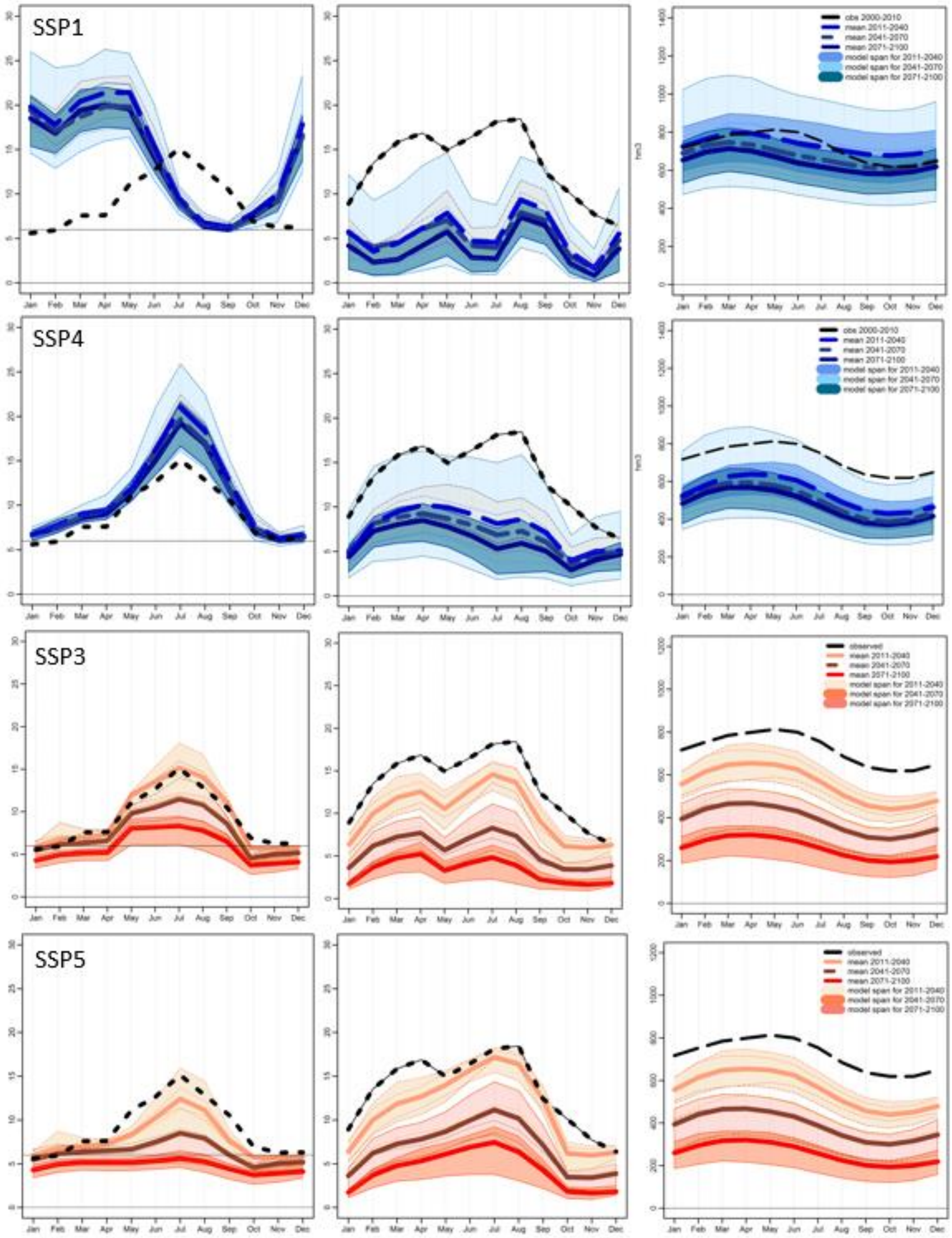


Figure 3.23: Long-term mean monthly discharge projections in the Tagus river under the SSP1xRCP4.5 (first row), SSP4xRCP4.5 (second row), SSP3xRCP8.5 (third row) and SSP5xRCP8.5 (fourth row) scenarios, after the Tagus Segura Transfer extraction (left column); of water supplied to the Segura Basin (middle column); and volume of the Buendia and Entrepenyas reservoirs (right column).

The critical level of the *Buendía* and *Entrepeñas* reservoirs of 400 hm^3, as defined by the Spanish authority, is reached after 2040 in SSP4xRCP4.5, SSP3xRCP8.5 and SSP5xRCP8.5, and is surpassed in 2070–2100 in both RCP8.5 scenarios (Figure 3.23). Likewise, while the volume and outflow of the Alcantara reservoir is maintained across time slices in SSP1xRCP4.5, these are projected to decrease significantly in the other three scenarios (e.g. up to 45% decreased outflow in 2011–2040). These drastic decreases, due to increased water withdrawals (e.g. increased water supply to Madrid and the organisation of a new transfer) and reduced water availability due to the impacts of high-end climate change, contribute to failure in meeting the Albufeira agreement.

3.3.2.2. *Hydropower production*

The discharge of the Tagus river basin is expected to decrease under both RCP4.5 and RCP8.5 climate change scenarios (Lobanova et al., 2016). Hydropower production generally decreases in the whole catchment due to decreasing water availability. Under RCP4.5, there is a slight decrease in the hydropower production potential (HPP) projected in the first time slice (2011–2040) followed by decreases of up to 27% and 45% in the 2041–2070 and 2071–2100 time slices, respectively.

Under RCP 8.5, slight decreases in HPP, for the first time slice (2011–2040) are projected to reach a minimum of 18% (multi-model mean) in November. In the following time slices, projected annual decreases of up to 35% (2041–2070) and 50% (2071–2100), based on a multi-model mean, are projected throughout the year. Since the two reservoirs, Buendía and Entrepeñas, are also used for the hydropower production this would potentially lead to a large decrease of the HPP at these sites under both RCP8.5 scenarios.

3.3.3. Model applications for agro-forestry

The LandClim model was applied to the four integrated climate and socio-economic scenarios to simulate changes in the agro-forestry systems typical of the Montado-Dehesa regions of Portugal and Spain. The baseline simulation used historic climate data from the WFDEI database to project cork and livestock production. Using this data, the model was run for 900 years to 'spin-up' the forested landscape from bare ground. The Montado forested landscape has two main tree species, *Quercus ilex* and *Quercus suber*. *Q. ilex* is a strong competitor in this landscape, and is actively harvested in favour of cork oak. Thus simulations also included a strong harvesting pressure on *Q. ilex* removing almost all stems in the landscape. For this spin-up period, an estimate of historical grazing pressure was made using stocking rates from the 1950s. This has been reported at 0.10 – 0.15 livestock units per ha (Sales-Baptista et al., 2015). After ~700 years, the landscape was fairly stable with regards to the tree cover, number of oak stems and cork production. Grazing pressure was then increased to current levels, reported at 0.94 livestock units per ha, for an average of 99 days. The model continued to run for another 60 years at this higher grazing pressure (roughly estimating the time period of 1950–2010).

The simulations of climate change scenarios all started in the year 2006 and took the final year of the baseline simulations (described above) as their starting point. LandClim was run for the next 94 years, until the end of the climate data in 2100. Current grazing pressure was maintained. Due to stochastic processes in LandClim, all scenarios were replicated 10 times. The baseline runs included tree management (selective harvesting of *Q. ilex*) and pasture management, but no fire. Fire suppression is a common practice, and wildfires are typically contained to small sizes.

Within this framework, LandClim was able to simulate cork production and grazing utilisation by cattle under current climate, and produce estimates of ecosystem service provisioning that correspond to observations for the study landscape (empirical cork production ~1100 kg/ha, simulated cork production for last 6 decades before the climate change simulations began, 1013–1057 kg/ha).

For pine plantations, the ForClim baseline simulation used historic climate from the WFDEI data to calculate the mean monthly temperatures, mean precipitation sums, and monthly cross-correlations between temperature and precipitation. Using this data, the ForClim model was run for 200-300 years (enough time to simulate at least 3 management cycles, depending on the species). It was assumed that the Maritime pine (*Pinus pinaster*) species was planted at a stem density of 1600 stems ha^{-1} and a final clear cut implemented at a tree age of 50 years.

As with the LandClim model, all scenario simulations started in the year 2006, with the start of a new management cycle (i.e. a planting from bare ground). The model simulated the next 94 years, until the end of the climate data in 2100.

3.3.3.1. *Cork and livestock production*

The baseline simulation (with current climate and a continuation of current grazing pressure) shows a slow decline in cork production until 2100 (Figure 3.24). This is linked to the reduction of *Q. suber* regeneration, as current grazing pressure is too high (Figure 3.25a). Cork production will therefore decrease even without climate change if grazing levels are maintained at current levels.

The SSP1 scenario combined an intermediate climate change scenario (RCP4.5 HadGEM2-ES-RCA4) with a reduction in livestock grazing, back to historical levels. The reduced grazing pressure results in an increase in tree regeneration (Figure 3.25b), which suggests a potential long-term recovery of some cork production after 2100 (i.e. as smaller trees recruit into larger size classes and produce cork), but this is beyond the length of the simulations. Under the SSP4xRCP4.5 scenario, with current grazing pressure, cork production declines show almost the exact same pattern as the scenario with historic grazing as presented in Figure 3.25a). Due to the higher grazing pressure, there are also higher utilisation rates, leading to more years throughout the century where grazing pressure is too high for tree regeneration and where forage production is not enough to sustain livestock (Figure 3.26).

Under SSP4, increasing drought frequency and intensity in the second half of the century cause a reduction in cork production (Figure 3.24a) due to higher drought-related mortality of adult trees. Even though there is still cork being produced at the end of the century, the reduction of cork oak tree regeneration suggests that cork production will continue to decline even further, indicating a much bleaker future for cork production. It is even more severe under the RCP8.5 scenario, with current grazing levels, with cork production showing a sharp decline in 2050 (Figure 3.24b) due to severe droughts causing the death of adult cork trees and additional droughts, in subsequent decades, kill virtually all cork oak trees resulting in no more cork being harvested after 2080 (Figure 3.27b).

In SSP4 there will also be an increasing number of years in the future where forage production is very low, and global stocking densities will exceed carrying capacity. Increasing drought intensity and frequency decreases forage production for livestock (causing an increase in utilisation rates and preventing oak trees from establishing). Even in the first half of the century, several severe droughts (shown by the spikes in Global Utilization (GU) in Figure 3.26) result in years which are not able to produce enough forage for livestock, and many years are not sustainable for tree regeneration (Figure 3.26b). In the second half of the century there are an increasing number of droughts, which increases the frequency of years where not enough forage is produced for livestock. Approximately half of the years between 2000-2100 will not produce enough grass to support livestock. However, in SSP1xRCP4.5, due to the reduced grazing pressure, it is only those extreme drought years where GU values are >1 (compare to Figure 3.26c with the same climate scenario, but current grazing pressure).

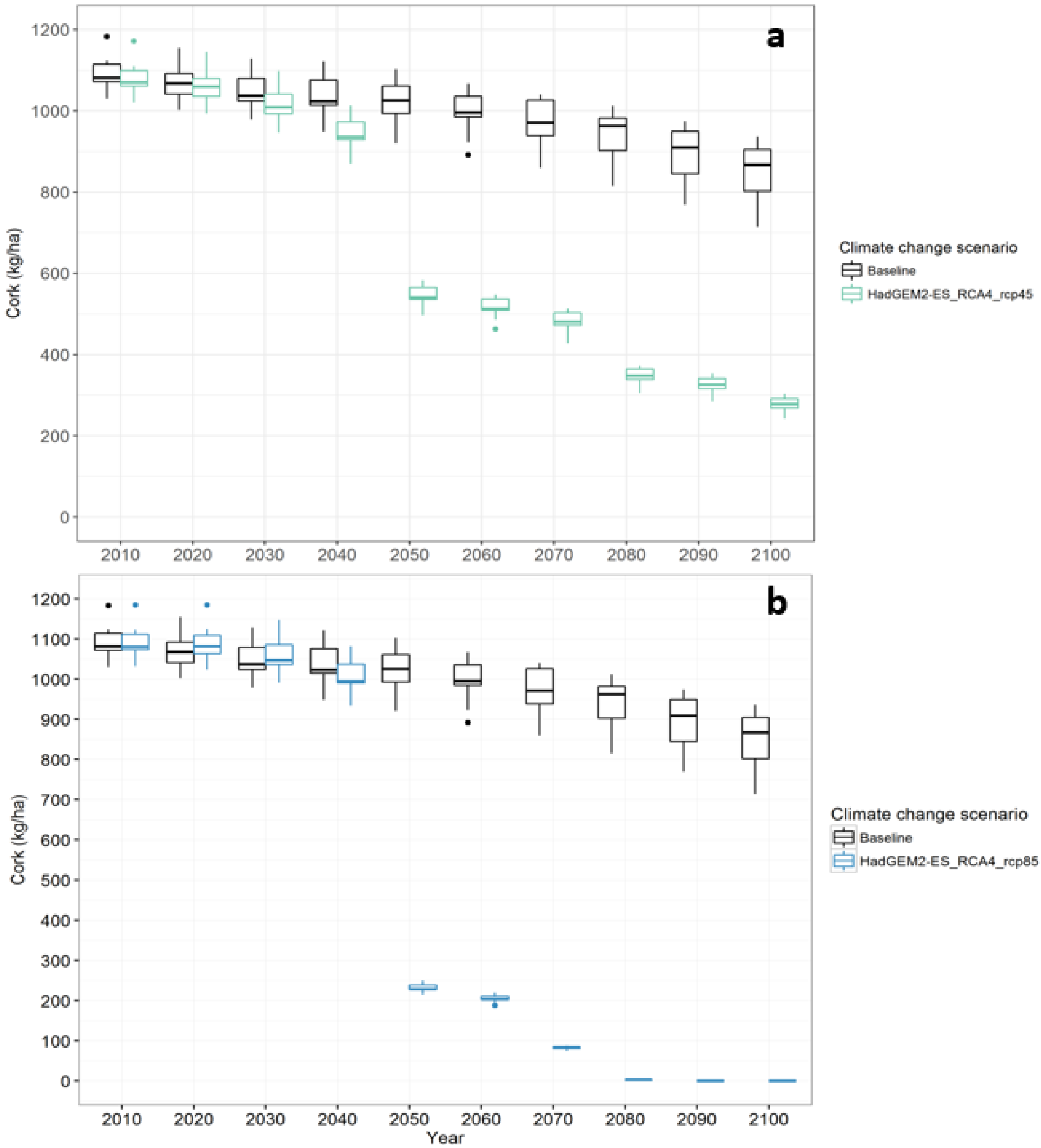


Figure 3.24: Cork production under (a) SSP1 (RCP4.5 HadGEM2-ES-RCA4 with reduced, historic grazing pressure), and (b) SSP3/SSP5 (RCP8.5 HadGEM2-ES-RCA4 with current grazing pressure). Baseline represents current climate with current grazing pressure. Cork was harvested every decade, and boxplots represent results from 10 replicated LandClim simulations.

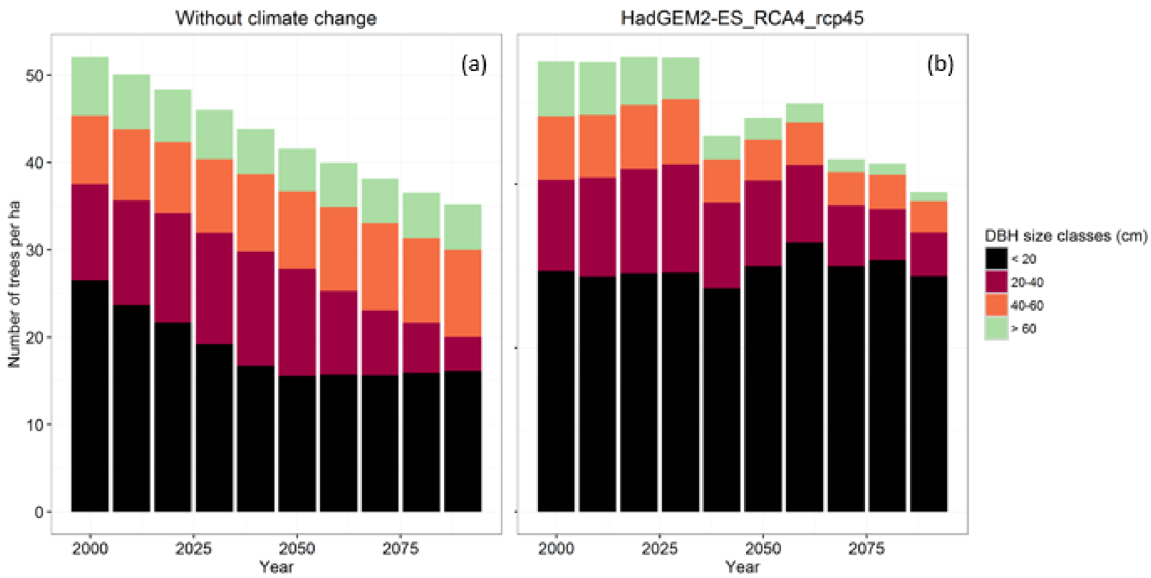


Figure 3.25: The number of cork oak trees per hectare in different size classes (DBH = diameter at breast height). Cork trees <20cm DBH (shown in black) represent the regenerating trees, and they are not harvested for cork. Shown are two simulations: (a) current climate with current grazing pressure and (b) SSP1xRCP4.5 assuming historic (lower) grazing pressure.

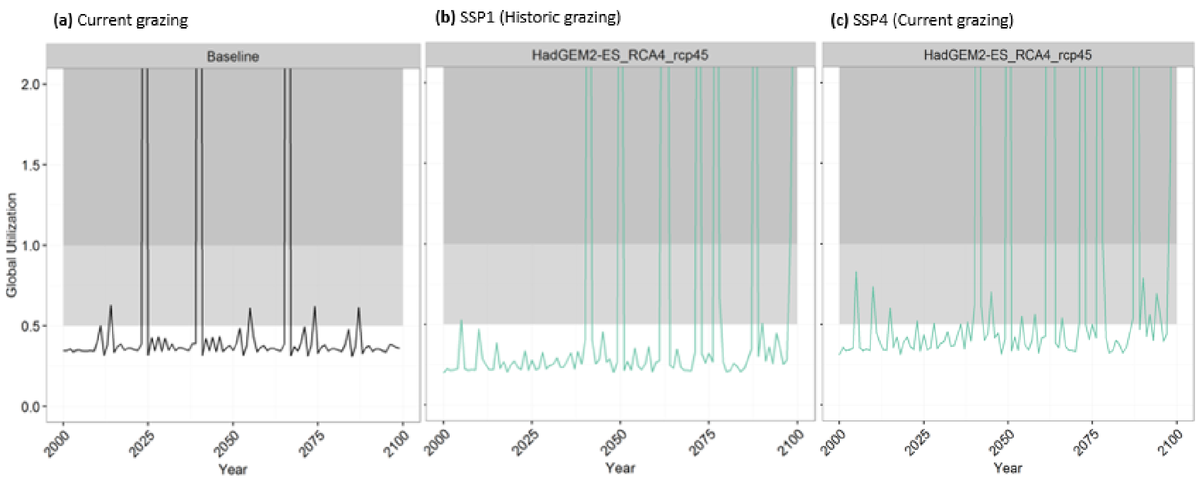


Figure 3.26: Global utilisation (global stocking density / global carrying capacity) each year for: (a) baseline conditions (current climate with current grazing); (b) SSP1 (RCP4.5 climate with historic grazing); and (c) SSP4 (RCP4.5 climate with current grazing pressure). Values above 0.5 are negative for tree regeneration (shown in light grey), and values above 1.0 are negative for trees and livestock (shown in dark grey).

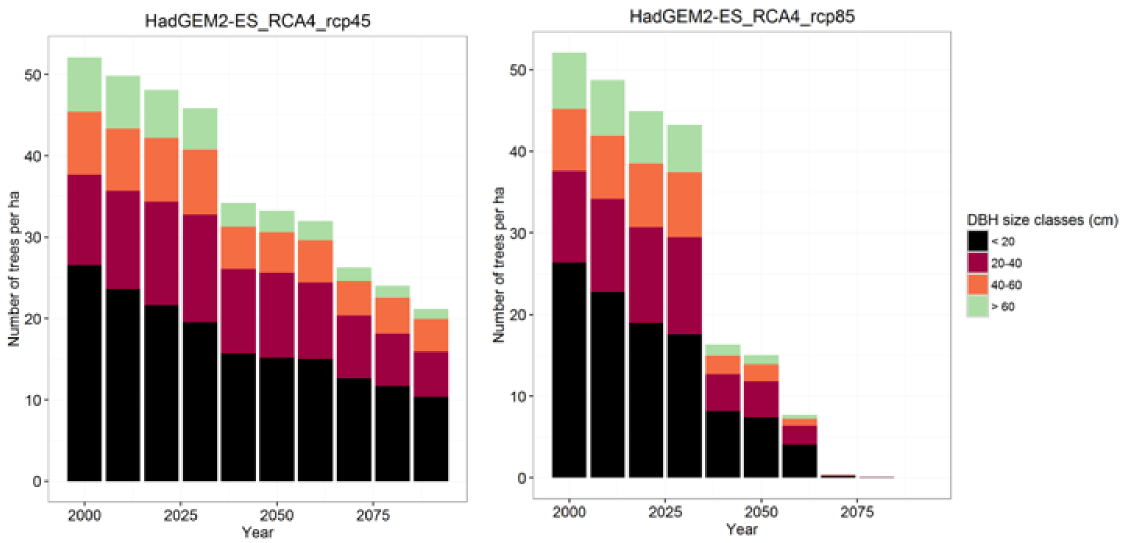


Figure 3.27: The number of cork oak trees per hectare in different size classes (DBH = diameter at breast height) simulated for RCP4.5 climate (left panel) and RCP8.5 climate (right panel), with current grazing pressure. Cork trees <20 cm DBH (shown in black) represent the regenerating trees, and they are not harvested for cork.

3.3.3.2. *Pine plantations*

During the first management cycle (from 2006–2056), many of the climate change scenarios show very similar growth and yield compared to the current climate, with some even showing improved yields (Figures 3.28 and 3.29). The intermediate climate change scenarios (RCP4.5) show comparable or even improved growth for the first half of the century, with only the least extreme climate model (MPI-ESM-LR_CCLM4_rcp45) matching baseline pine productivity until 2100, and all other scenarios showing a reduction in the volume of pine produced (Figure 3.28).

While some of the RCP4.5 scenarios show a reduction in the final harvested volume, the RCP8.5 scenarios show little growth during the second management cycle (from 2056–2100; Figure 3.29). One of the high-end scenarios (IPSL-CM5A-MR_WRF_rcp85) shows almost no growth of pine even in this first management cycle. Therefore, under the most severe climate change scenarios, pine is unable to establish or grow due to increasing droughts. The difference between the climate change scenarios is driven by increasing drought frequency and intensity, as this is the main limiting factor for both growth and establishment.

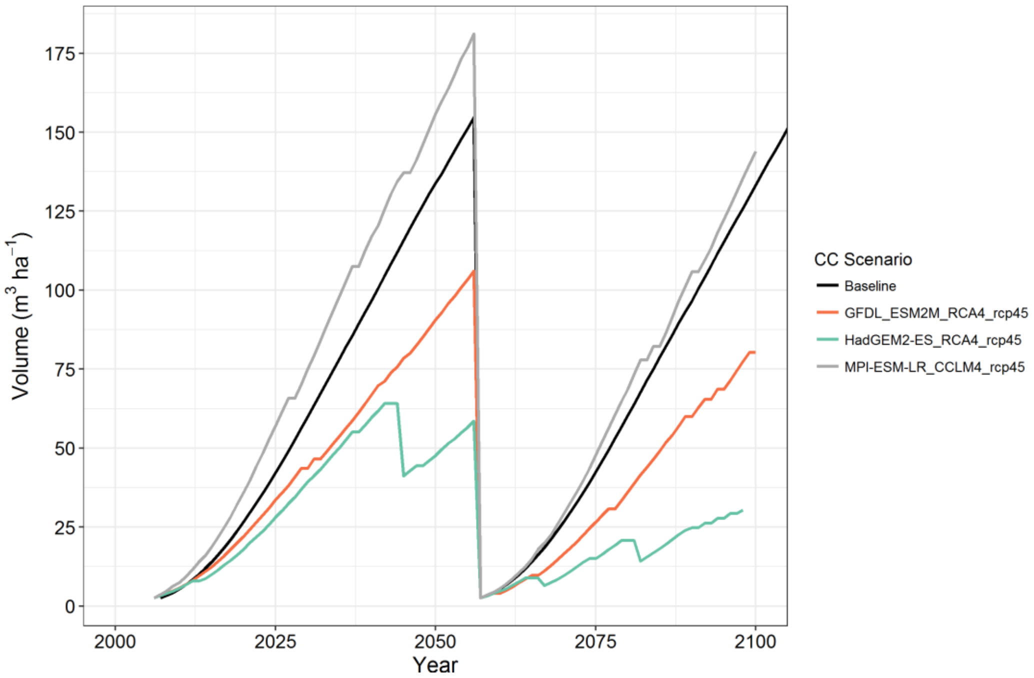


Figure 3.28: Simulated volume of *Pinus pinaster* plantations under current climate (baseline) and three RCP4.5 climate change scenarios. All forests were planted with 1600 seedlings in the year 2006 and then forests were harvested with a clear cut at 50 years of age.

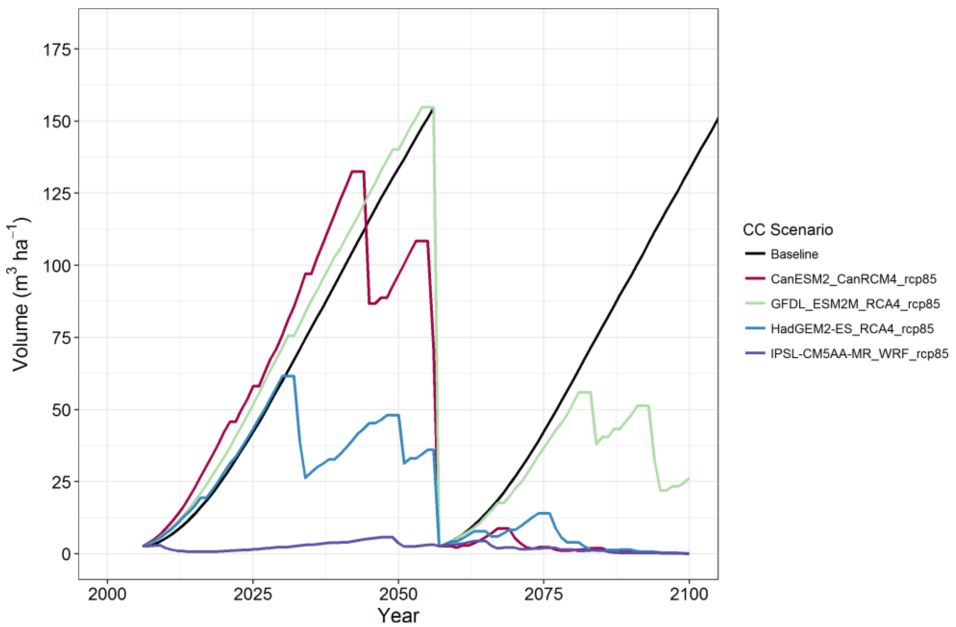


Figure 3.29: Simulated volume of *Pinus pinaster* plantations under current climate (baseline) and four RCP8.5 climate change scenarios. All forests were planted with 1600 seedlings in the year 2006 and then forests were harvested with a clear cut at 50 years of age.

3.3.4 Summary of cross-sectoral issues and vulnerability

The modelling results for Iberia project significant changes in annual and seasonal precipitation, with uncertainties in both the strength of the change signal and its seasonal variations. From these results it is evident that the Iberian Peninsula and the Tagus river basin area, in particular, will continue on their current trend towards a drier and more vulnerable landscape. Seasonal variability is expected to play a major role in the socio-economic outcomes under high-end climate change scenarios since current water resources and agroforestry management in that area is highly dependent on accumulated precipitation during the hydrological year (October to September), in particular during its wet period (October to April).

A changing climate coupled with shifting land use and water management practices has the potential to alter the socio-ecological balance of the entire region. The level of projected cross-sectoral vulnerabilities is highly dependent on the socio-economic scenario. For example, vulnerabilities associated with decreases in future water availability in the Tagus area differ substantially under different socio-economic narratives, even under the same climate scenario. This is valid for hydropower (river basin discharge), pine, and cork and livestock production. The latter two can potentially decrease significantly even under a less extreme climate change signal, if current management practices are maintained.

Increasing drought frequency and intensity throughout the century under all scenarios, is expected to greatly influence the provisioning of multiple interacting ecosystem services related to agro-forestry landscapes and water. High-end climate change scenarios will prompt the need for changes in land use management planning and the consideration of novel management options. Associated decision-making timings may range from now to mid-century, depending on the SSP narrative. These results point out that high-end climate change has the potential to be highly influential in the way Iberian societies need to interact with their landscapes, and should serve as a basis for reflection on both the risks and opportunities within the land/water sectors and on the specific needs that different mitigation and adaptation pathways may entail.

4. Discussion

4.1. Overview of CCIAV model applications in the regional/local case studies

A wide range of CCIAV models have been applied in the three regional/local case studies. The model applications were selected to match the key challenges related to high-end climate change in each case study in consultation with local stakeholders. A summary of model applications across the case studies is given in Table 4.1. All case studies covered challenges related to land resources under high-end climate change. The Hungarian and Scottish case studies focused on urban and agricultural land use, whilst the Iberian and Scottish case studies covered forestry or agro-forestry. All case studies also covered challenges related to water resources. These challenges varied depending on the case study from severe water stress in Iberia and Hungary to potential flooding in Scotland. In addition, Hungary and Scotland assessed impacts related to human health and well-being, in particular Lyme disease risk and heat-related mortality; the latter only being relevant to Hungary.

Table 4.1: CCIAV model applications in the three regional/local case studies.

Key challenges	Hungary	Scotland	Iberia
Land resources:			
Urban land use	√	√	
Agricultural land use	√	√	
Forestry		√	√
Agro-forestry			√
Wine sector		√	
Tourism		√	
Water resources:			
Water availability	√	√	√
Hydropower production			√
Flooding		√	
Human well-being:			
Heat-related mortality	√		
Lyme disease risk	√	√	

Findings from model applications vary widely by the integrated RCP x SSP scenario and by case study. Impacts were generally less severe under the scenarios associated with intermediate (RCP4.5) rather than high-end (RCP8.5) climate change. However, impacts under intermediate climate change scenarios were often still highly detrimental, particularly for water availability in Iberia and heat stress in Hungary. Impacts also varied considerably by socio-economic scenario (SSP), with impacts generally being less negative under the sustainability-focused SSP1 scenario compared with the highly fragmented SSP3 or fossil-fuel intensive SSP5 scenarios. For example, SSP1 was projected to result in moderate increases in compact urban development patterns, whilst SSP5 resulted in large increases in sprawled urban development in both Hungary and Scotland. Similarly, increases in heat-related mortality in Hungary were least under SSP1 and greatest under SSP5, although this is due to a mix of socio-economic and climate effects. Likewise for Iberia, water availability was projected to decrease the least under SSP1 due to advances in the efficiency of water withdrawals and more efficient water use, and decrease the most under SSP3 and SSP5 due to increased water withdrawals and the severe impacts of high-end climate change on water availability in the catchment.

Impacts on land and water resources are highly inter-related as land use patterns are influenced by water availability and its allocation to meet (or not) demand from different sources (e.g. domestic/industrial, irrigation, hydropower, etc.). Impacts on land and water resources also affect human health and well-being. These cross-sectoral vulnerabilities are highly dependent on the socio-economic scenario. Each scenario narrative contains different assumptions about how society manages different land, water and energy resources and their competing demands, including what resources (e.g. food production, forestry, biodiversity protection and ecosystem service provision) are prioritised and how trade-offs may or may not be balanced. Ultimately the impacts under the four integrated scenarios show that the choices made by decision-makers and societal actors will lead to large differences in future impacts. These differential impacts demonstrate the range of both opportunities and potential risks associated with high-end climate change and can aid stakeholders, by informing discussions, in exploring potential adaptation and mitigation pathways.

4.2. Uncertainties in CCIAV model applications

4.2.1. Climate model uncertainty

The applications presented here all rely on a limited set of climate change scenarios. The scenarios were selected to represent intermediate and high levels of global climate change. All models agree that temperature increases in the future, but the degree of change depends on the future emission scenario as well as the specific climate model. The uncertainty in precipitation changes is generally larger than for temperature.

For the impacts simulated using the IMPRESSIONS IAP2, the HadGEM-RCA4 model has been used as the default model and combined with emissions reflecting RCP4 and RCP8.5; the HAdGEM-RCA4 projects a relatively large climate change signal for a given emission scenario as seen in Table 2.1. In these cases uncertainties related to the choice of climate model are not explored. The process-based models generally used the full subset of seven climate models from Table 2.1 to explore climate model uncertainty.

The influence of climate model uncertainty depends strongly on the sensitivity of the impact model to differences in projected climate change (e.g. seasonal changes in precipitation patterns). It should be emphasised that the seven climate models only make up a small subset of the full climate model ensemble; the local spread of projected temperature and precipitation changes would most certainly be larger if more climate models were included. It should also be noted that averaging over the selected subset may give results significantly different from those obtained from using the full ensemble. These issues will be explored in more detail in Deliverable D2.4 on integrated multi-scale scenarios (due in October 2017) and Deliverable D3.2 on cross-scale comparison of modelling applications (due in December 2017).

4.2.2. Impact model uncertainty

Impact models themselves are a widely acknowledged and inherent source of uncertainty within the overall cascade of uncertainty in climate change impact assessments. This uncertainty results from the imperfect ability of an impact model to reproduce reality due to a combination of uncertainty in model inputs and observations, model structure error and/or model parameterisation uncertainty (Remesan and Holman, 2015). All of the impact models applied in the regional case studies have been calibrated and validated against a range of observed data, and model performance reported. For example, the ability of the physically-based SWIM ecohydrological model to reproduce observed river flows in the three regional case studies has been shown (Table 2.4 and Figures 3.10, 3.18 and 3.21), with Nash-Sutcliffe Efficiency of 0.66 and 0.74 reported for the simulated storage volume within the Buendía and Entrepeñas reservoirs in the Tagus river within the Iberian regional case study (Lobanova et al., 2017).

The differences in simulated outputs due to model structure have been explored using regional case studies' SWIM model and ForClim model through comparison with the computationally simpler emulator-based models used in the European case study (Deliverable D3B.1 - Holman et al., 2015). Finally, the impact models within the IAP2 used in the Scottish regional case study have previously undergone extensive uncertainty analysis, both with regards to the impact models (e.g. Dunford et al. 2015), the propagation of parameter uncertainty (e.g. Brown et al., 2015) and the differences between applying models in a stand-along and integrated frameworks (Harrison et al., 2016). Impact model uncertainty assessment is ongoing and the comparison and analysis of results from the CCIAV models and methods across multiple (global, European and regional) scales will be reported in Deliverable D3.2 ‘Comparison of modelling results across scales’ (due in December 2017).

4.2.3. Uncertainty in quantification of scenario narratives

Scenario narratives integrate imagination in strategic thinking and, as such, provide a “bridge” between analytical thinking and creative visioning (Rasmussen 2005). Because narratives provide “holistic views” of the future and transcend the sum of single parts (Rasmussen 2005), it becomes very complex to reduce narratives to a selection of model variables. By definition, models cannot (yet) reproduce the whole complexity captured by scenario narratives. By acknowledging this gap, Pedde et al. (in review) argue that narratives can be bridged to models, while maintaining their original characteristics and purposes. The regional case studies have focused on bridging narratives created in a “co-production” context, where stakeholders with different backgrounds are professionally facilitated in a process that promotes creative, exploratory individual thinking and brainstorming, which leads to agreement on shared assumptions (Pedde et al., in review).

Because of the complex process which leads to the final narratives, the interpretation of the meaning of the narratives remains vague and cannot be captured by a simple extrapolation of quantitative trends from the same narrative text (Pedde et al., in review). For this reason, both stakeholder-led and expert-led scenario quantification exercises were undertaken. Expert judgement was necessary for a number of reasons: (i) the workshop setting does not allow for more variables to be quantified - a trade-off is therefore inevitable due to time and resource constraints; and (ii) some variables are too specific for quantification by a broad panel of stakeholders and therefore expert judgement remains preferable. Even in this case, key stakeholder-led variables *de facto* contribute to the interpretation of other model variables, therefore, further increasing consistency between narratives and model input.

4.2.4. Challenges at the qualitative-quantitative interface

Beyond the uncertainties arising from the descriptive nature of scenario narratives and specificity required by modelling, exploring the relationship between socio-economic development trajectories and climate futures has to tackle other challenges. The uncertainties are manifested through the need to translate qualitative judgments into quantifiable model variables or coefficients at various stages of the assessment process. These uncertainties are minimised through the use of participatory group methods within the professionally facilitated stakeholder workshops and within project team meetings. These involve experts or stakeholders revealing their informed, but essentially subjective, judgments about an aspect of the scenario and its impacts, which usually with the help of a moderator leads to a consensus view that is recorded as a result.

However, apart from the fact that even with the use of participatory methods the cascade of uncertainties leads to *compound* uncertainty, out of methodological and conceptual necessity the results are captured through simplified narratives and models. Despite their computational complexity, models typically further distill narratives into a small number of quantitative indicator projections captured through numbers and related visuals. While these artefacts of a complex scenario process can be useful for analytic and communication purposes, they offer almost no sensory experience of the texture of the future they represent. Reducing scenario results to numbers and technical visuals and text is not only a matter of aesthetics: the transformation embedded in some of the scenarios clearly require going beyond what Char Davies refers to as “an unconscious bias of a given culture” (Davies, 2003). In order to address and, at least at the symbolic level, transcend the simplifications and potential 'unconscious bias' embedded in the scenarios, the case studies in Hungary and Iberia made use of art in various forms and in various stages of the scenario process.

In the Hungarian case study scenario narratives and quantitative projections were captured through paintings by a noted artist (Figure 4.1). The images were developed on the basis of initial scenario narratives as a starting point, but they were also used to navigate the process as impacts associated with scenarios were explored in quantitative terms and as measures were identified for adaptation and mitigation pathways. The images did not simply objectify scenarios or specific aspects, but also allowed participants to immerse in a familiar and often upsetting or inspiring aspect of the scenario built around familiar landscapes and objects reconfigured according to the scenario logic.

Figure 4.1: Scenario illustrations from the Hungarian case study (Clockwise from top left: SSP1 - Rózsaszin álom; SSP3 – Regional rivalry; SSP5 - Pató Pál úr; SSP4 – Inequality).

The case study in Iberia used theatre and conceptual installations both with objects and actors to expose participants to the conundrum presented by high-end climate change as an integral part of scenario construction. The conceptual art installation involved the creation of a scenario space that symbolised four alternative future trajectories projected from the central point of the present (Figure 4.2). The installation was used as a participatory space for exploring scenario texture and pathway development.

Figure 4.2: Scenario space as a conceptual art installation in the Iberian case study.

The other example from the Iberian case study involved an installation with live actors to illustrate the challenge of addressing high-end climate change as a wicked problem (Figure 4.3). The process involved scenario developers in physically disentangling the installation to enact the process of transition and the development of adaptation pathways.

Figure 4.2: Installation to symbolise high-end climate change as a wicked problem.

Breaking out of the "drama of unsustainability" calls for sustainability science to transcend the epistemological underpinnings and worldviews involved in creating knowledge and envisioning actions that open up pathways towards transformative change (Heras and Tàbara, 2014). The examples in the Hungarian and Iberian case studies served demonstrative purposes to show the potential of complementing quantitative climate and sustainability science with methods that enrich the texture of scenarios and bring the experience of transformation closer to the personal level of participants.

4.3. Next steps for the regional/local CCIAV modelling

The CCIAV modelling applications presented in this deliverable focus on impacts and vulnerability under the four integrated climate and socio-economic scenarios in the three case studies. As described in Section 2.4 these impacts were presented to stakeholders during the second set of case study workshops to prompt stakeholders to suggest adaptation, mitigation and transformation actions to address the simulated vulnerabilities and risks. WP4 has been analysing the suggested actions to create a set of proto-pathways associated with each integrated scenario. The combination of actions is currently being modelled to assess the degree to which they help move society in each of the scenarios towards their desirable vision of the future. This work is ongoing and being presented to stakeholders during the third set of workshops, which at the time of writing are only partially completed. This assessment of the effectiveness of adaptation actions within the pathways to ameliorate climate change impacts and vulnerabilities will be described in full in Deliverable D4.2 (due in October 2017). Preliminary results from the Scottish case study, which held its third stakeholder workshop in June 2017 are shown in Figure 4.4.

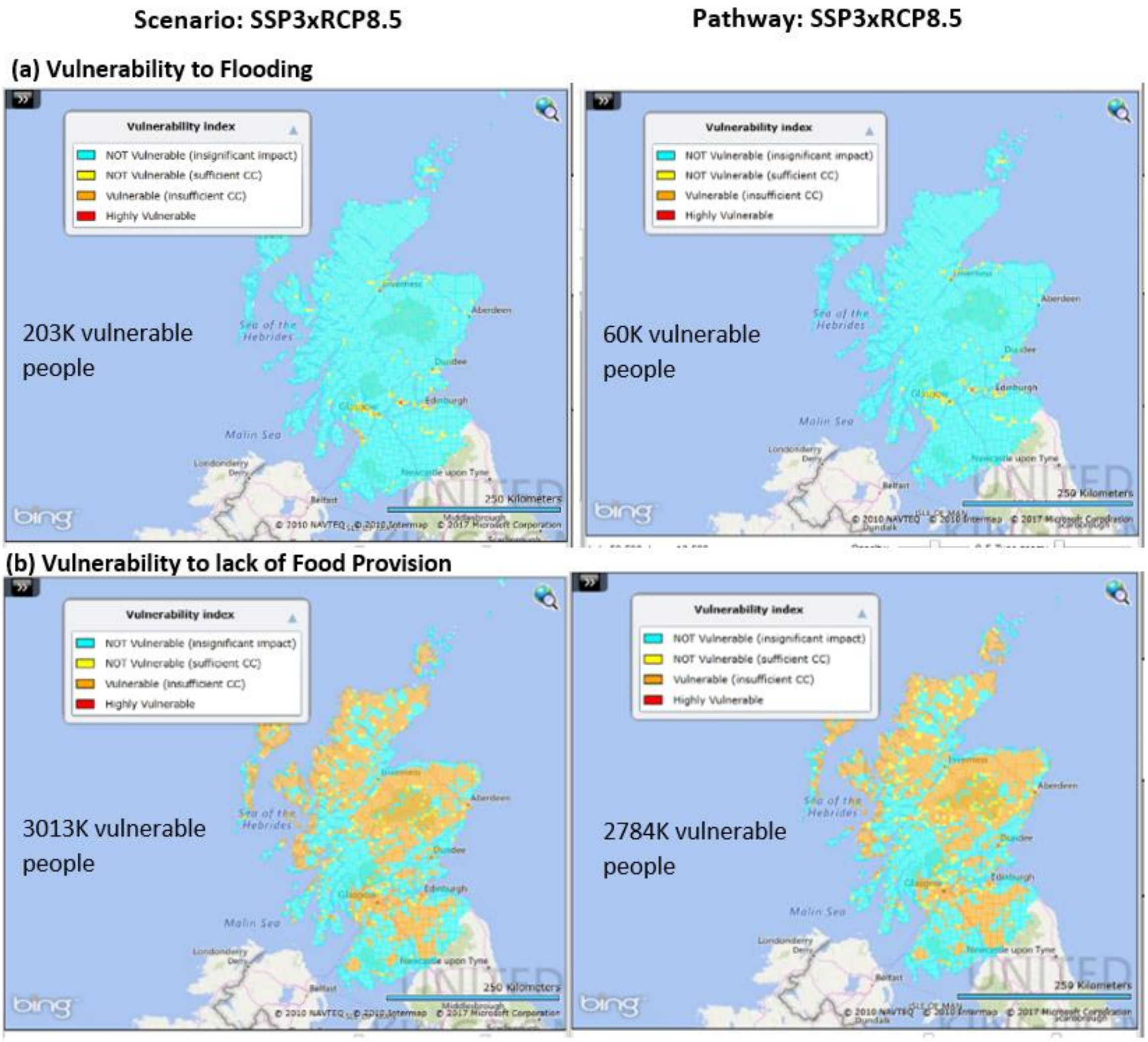


Figure 4.4: Effects of adaptation actions within the pathways associated with the SSP3xRCP8.5 integrated scenario on: (a) vulnerability to flooding; (b) vulnerability of a lack of food provision. Impacts under the integrated scenario with no adaptation (left column) and impacts under the integrated scenario with combined adaptation actions from the pathways (right column).

Stakeholders participating in the third set of workshops will elaborate and finalise the proto-pathways. These will then be re-assessed using the CCAIV models and the qualitative assessment described in Section 2.4 to see if the additional adaptation, mitigation or transformation actions helps move society even closer to their vision under each integrated scenario. The third set of stakeholder workshops will also compare actions across scenarios to see which are robust to different futures.

Finally, selected stakeholders from the different case studies (the three regional/local case studies described here and the European and Central Asian case study) will be invited to the final cross-scale stakeholder workshop (April 2018) to compare experiences across case studies and scales of assessment. This will inform which pathways (and actions within them) are common across case studies and scales, and which are context dependent. In preparation for the cross-scale workshop, WP3 will undertake a comparison of modelling results across case studies and scales, including an assessment of different sources of uncertainty on the modelling outcomes. This will be reported in Deliverable D3.2 (due in December 2017).

5. Acknowledgements

We are grateful to numerous colleagues in the IMPRESSIONS project for their support of the work that provides the basis of this deliverable. The case study leaders and their teams have contributed to the identification of key challenges under high-end climate change to which model applications have been matched. Modelling colleagues working at the global and European scales have provided valuable input and advice on the regional/local scale modelling applications. Colleagues from other IMPRESSIONS work packages have provided valuable input and support on decision-maker needs (WP1), scenarios (WP2), pathways (WP4), synthesis and transformation (WP5), and stakeholder engagement (WP6A). Finally, we are very grateful to the stakeholders who participated in the workshops and provided us with feedback on the modelling applications and the pathways of actions for addressing high-end climate and socio-economic change.

6. References

Audsley, E., Pearn, K.R., Simota, C., Cojocaru, G., Koutsidou, E., Rounsevell, M.D.A., Trnka, M., Alexandrov, V. (2006) What can scenario modelling tell us about future European scale agricultural land use, and what not? *Environmental Science & Policy* 9, 148–162.

Audsley, E., Trnka, M., Sabaté, S., Sanchez, A. (2015) Interactive modelling of land profitability to estimate European agricultural and forest land use under future scenarios of climate, socio-economics and adaptation. *Climatic Change* 128, 215–227.

Brown, C., Brown, E., Murray-Rust, D., Cojocaru, G., Savin, C., Rounsevell, M.D.A. (2015). Analysing uncertainties in climate change impact assessment across sectors and scenarios. *Climatic Change*, 128, 293–306. [doi: 10.1007/s10584-014-1133-0]

Bugmann, H. (2001) A review of forest gap models. Climatic Change 51, 259-305.

Bugmann, H., Solomon, A.M. (2000) Explaining forest composition and biomass across multiple biogeographical regions. *Ecological Applications* 10, 95–114.

Carter, T.R, Rounsevell, M.D.A., Fronzek, S., Harrison, P.A., Holman, I.P., Pirttioja, N.K. (2015) Integrated assessment approach. EU FP7 IMPRESSIONS Project Deliverable D3.1. Available from www.impressions-project.eu

Carter TR, Fronzek S, Alkemade R, Holman I, Honda Y, Ito A, Jäger J, Leemans R, Nunez S, Oka K, O'Neil N, Onigkeit J, Pedde S, Rounsevell M, Takahashi K, Wimmer F, Yoshikawa M (2016). Global scale application of climate change impact, adaptation and vulnerability (CCIAV) models. EU FP7 IMPRESSIONS Project Deliverable D3A.1.Available from www.impressions-project.eu.

Central Statistical Office (2016) Mezőgazdaság számokban [Agriculture in numbers] Gazdaságszerkezeti összeírás. Central Statistical Office, Budapest, Hungary.

Christensen, O.B., Drews, M., Christensen, J.H., Dethloff, K., Ketelsen, K., Hebestadt, I., Rinke, A. (2006) The HIRHAM Regional Climate Model. Version 5. DMI Technical Report No. 06-17.

Davies, C. (2003) Landscape, earth, body, being, space and time in the immersive virtual environments osmose and ephémère. In Women, Art, and Technology. Judy Malloy, ed. Cambridge, MA and London, England: MIT Press, pp. 322–337.

Dunford, R., Harrison, P.A., Rounsevell, M.D.A. (2015) Exploring scenario and model uncertainty in cross-sectoral integrated assessment approaches to climate change impacts. *Climatic Change* 132, 417–432. [doi: 10.1007/s10584-014-1211-3]

Dunn, M., Rounsevell, M.D.A., Boberg, F., Clarke, E., Christensen, J., Madsen S.M. (*in review*). The future potential for wine production in Scotland under high-end climate change.

Dunn, M., Rounsevell, M.D.A., Carlsen, H., Dzebo, A., Capela Lourenço, T., Hagg, J. (2017) To what extent are land resource managers preparing for high-end climate change in Scotland? *Climatic Change* 141, 181–195 [doi: 10.1007/s10584-016-1881-0]

Elkin, C., Gutiérrez, A.G., Leuzinger, S. *et al.* (2013) A 2 °C warmer world is not safe for ecosystem services in the European Alps. *Global Change Biology* 19, 1827–1840 [doi: 10.1111/gcb.12156]

Fischer, G., van Velthuizen, H., Shah, M., Nachtergaele, F. (2002) Global agro-ecological assessment for agriculture in the 21st Century: Methodology and results. International Institute for Applied Systems Analysis, Laxenburg, Austria.

Flörke M., Kynast, E., Bärlund, I., Eisner, S., Wimmer, F., Alcamo, J. (2013) Domestic and industrial water uses of the past 60 years as a mirror of socio-economic development: A global simulation study. *Global Environmental Change* 23, 144–156.

Fronzek, S., Carter, T.R., Räisänen, J., Ruokolainen, L., Luoto, M. (2010) Applying probabilistic projections of climate change with impact models: a case study for sub-arctic palsa mires in Fennoscandia. *Climatic Change* 99, 515–534 [doi:10.1007/s10584-009-9679-y]

Gasperrini, A., Armstrong, B., Kenward, M.G. (2010) Distributed lag non-linear models. *Statistics in Medicine* 29, 2224–2234.

Gracia, C., Tello, E., Sabaté, S., Bellot, J. (1999) GOTILWA: An integrated model of water dynamics and forest growth. In Rodà F, Retana J, Gracia C, Bellot J, eds Ecology of Mediterranean evergreen oak forests. Springer, Berlin, pp. 163–179.

Harrison, P.A., Berry, P.M., Butt, N., New, M. (2006). Modelling climate change impacts on species' distributions at the European scale: Implications for conservation policy. *Environmental Science and Policy* 9, 116–128.

Harrison, P.A., Holman, I.P., Berry, P.M. (2015). Assessing cross-sectoral climate change impacts, vulnerability and adaptation: an introduction to the CLIMSAVE project. *Climatic Change* 128, 153–167.

Harrison, P.A., Dunford, R., Holman, I.P., Rounsevell M.D.A. (2016). Climate change impact modelling needs to include cross-sectoral interactions. *Nature Climate Change* 6, 885. [doi: 10.1038/nclimate3039]

Hartmann, J., Moosdorf, N. (2012) The new global lithological map database GLiM: A representation of rock properties at the Earth surface. *Geochemistry, Geophysics, Geosystems* 13, Q12004.

Hazeleger, W., Wang, X., Severijns, C., Ştefănescu, S., Bintanja, R., Sterl, A., Wyser, K., Semmler, T., Yang, S., van den Hurk, B., van Noije, T., van der Linden, E., van der Wiel, K. (2012) EC-Earth V2.2: description and validation of a new seamless earth system prediction model. *Climate Dynamics* 39, 2611–2629. [doi:10.1007/s00382-011-1228-5]

Henne, P.D., Elkin, C., Colombaroli, D., Samartin, S., Bugmann, H., Heiri, O., Tinner, W. (2013) Impacts of changing climate and land use on vegetation dynamics in a Mediterranean ecosystem: insights from paleoecology and dynamic modelling. *Landscape Ecology* 28, 819–833.

Henne, P.D., Elkin, C., Franke, J., Colombaroli, D., Calò, C., La Mantia, T., Pasta, S., Conedora, M., Dermody, O., Tinner, W. (2015) Reviving extinct Mediterranean forest communities may improve ecosystem potential in a warmer future. *Frontiers in Ecology & Environment* 13, 356–362.

Heras, M. and Tàbara, J. D. (2014) Let's play transformations! Performative methods for sustainability. *Sustainability Science* 9, 379–398.

Holman, I., Harrison, P.A. (2012) Report describing the development and validation of the sectoral meta-models for integration into the IA platform. CLIMSAVE Deliverable D2.2. Available from http://www.climsave.eu/climsave/doc/Report_on_the_Meta-models_updated.pdf.

Holman, I., Audsley, E., Berry, P., Brown, C., Bugmann, H., Clarke, L., Cojocaru, G., Dunford, R., Harrison, P.A., Janes, V., Kovats, S., Lafond, V., Li, S., Lobanova, A., Mokrech, M., Rounsevell, M., Sandars, D., Savin, C., Wimmer, F. (2015) Specification for European model improvement and development. EU FP7 IMPRESSIONS Project Deliverable D3B.1. Available from www.impressions-project.eu

Holman, I., Audsley, E., Berry, P., Brown, C., Bugmann, H., Clarke, L., Cojocaru, G., Dunford, R., Fronzek, S., Harrison, P.A., Honda, Y., Janes, V., Kovats, S., Lafond, V., Lobanova, A., Madsen, M.S., Mokrech, M., Nunez, S., Pedde, S., Sandars, D., Savin, C., Wimmer, F. (2017) Modelling climate change impacts, adaptation and vulnerability in Europe. EU FP7 IMPRESSIONS Project Deliverable D3B.2. Available from www.impressions-project.eu

Honda, Y., Kondo, M., McGregor, G., *et al*. (2014) Heat-related mortality risk model for climate change impact projection. *Environmental Health & Preventative Medicine* 19, 56–63. [doi: 10.1007/s12199-013-0354-6]

Ito, A., Inatomi, M. (2012) Water-Use Efficiency of the Terrestrial Biosphere: A Model Analysis Focusing on Interactions between the Global Carbon and Water Cycles. *Journal of Hydrometeorology* 13, 681–694. [doi: 10.1175/JHM-D-10-05034.1]

Kok K, Hesselbjerg Christensen J, Sloth Madsen M, Pedde S, Gramberger M, Jäger J & Carter T (2015). Evaluation of existing climate and socio-economic scenarios. EU FP7 IMPRESSIONS Project Deliverable D2.1. Available from www.impressions-project.eu

Kok, K., Pedde, S. (2016) IMPRESSIONS socio-economic scenarios. EU FP7 IMPRESSIONS Project Deliverable D2.2. Available from www.impressions-project.eu

Li, S., Gilbert, L., Harrison, P.A., Rounsevell, M.D.A. (2016) Modelling the seasonality of Lyme disease risk and the potential impacts of a warming climate within the heterogeneous landscapes of Scotland. *Journal of The Royal Society Interface* 13, 20160140. [doi: 10.1098/rsif.2016.0140]

Lobanova A, Koch H, Liersch S, Hattermann FF, Krysanova (2016) Impacts of changing climate on the hydrology and hydropower production of the Tagus River basin. *Hydrological Process* 30, 5039–5052. [doi: 10.1002/hyp.10966]

Lobanova A, Liersch S, Tabara JD, Koch H, Hattermann FF, Krysanova (2017) Harmonizing human-hydrological system under climate change: A scenario-based approach for the case of the headwaters of the Tagus River. *Journal of Hydrology* 548, 436–447. [doi: /10.1016/j.jhydrol.2017.03.015]

Lucas-Picher, P., Boberg, F., Christensen, J.H., Berg, P. (2013) Dynamical downscaling with reinitializations: a method to generate fine-scale climate data sets suitable for impact studies, *Journal of Hydrometeorology* 14, 1159–1174. [doi: 10.1175/JHM-D-12-063.1]

Masutomi, Y., Takahashi, K., Harasawa, H., Matsuoka, Y. (2009) Impact assessment of climate change on rice production in Asia in comprehensive consideration of process/parameter uncertainty in general circulation models. *Agriculture, Ecosystems & Environment* 131, 281–291.

Mokrech M., Nicholls R.J., Richards J.A., Henriques C., Holman I.P., Shackley S. (2008) Regional impact assessment of flooding under future climate and socio-economic scenarios for East Anglia and North West England. *Climatic Change* 90, 31–55.

Mokrech, M., Kebede, A.S., Nicholls, R.J., Wimmer, F., Feyen, L. (2015) An integrated approach for assessing flood impacts due to future climate and socio-economic conditions and the scope of adaptation in Europe. *Climatic Change* 128, 245–260.

Murray-Rust, D., Robinson, D.T., Guillem, E., Karali, E., Rounsevell, M. (2014) An open framework for agent based modelling of agricultural land use change. *Environmental Modelling & Software* 61, 19–38. [doi: 10.1016/j.envsoft.2014.06.027]

Pedde, S.K., *et al* (in review) Bridging uncertainty concepts across narratives and simulations in environmental scenarios. *Regional Environmental Change*.

Prudhomme, C., Wilby, R.L., Crooks, S., Kay, A.L., Reynard, N.S. (2010) Scenario-neutral approach to climate change impact studies: Application to flood risk. *Journal of Hydrology* 390, 198–209 [doi: 10.1016/j.jhydrol.2010.06.043]

Rasmussen L.B.(2005) The narrative aspect of scenario building - How story telling may give people a memory of the future. *AI & Society* 19, 229–249. [doi:10.1007/s00146-005-0337-2]

Reginster, I., Rounsevell, M. (2006) Scenarios of future urban land use in Europe. *Environment and Planning B: Urban Analytics and City Science* 33(4), 619–636.

Remesan, R, Holman I (2015) Effect of baseline meteorological data selection on hydrological modelling of climate change scenarios. *Journal of Hydrology* 528, 631–642

Richter, B., Baumgartner, J. (1997) How much water does a river need? *Freshwater Biology* 37, 231–249.

Rounsevell, M., Clarke, E., Dunn, M., Bugmann, H., Cojocaru, G., Joao Cruz, M., Harrison, P.A., Horvath, L., Khare, S., Kovats, S., Krysanova, V., Lafond, V., Li, S., Lobanova, A., Capel Lourenco, T., Sloth Madsen, M., Pedde, S., Pinter, L., Snell, R., Savin, C., Tabara, D., Terama, E. (2015) Specification of regional/local scale models and methods. EU FP7 IMPRESSIONS Project Deliverable D3C.1. Available from www.impressions-project.eu

Sales-Baptista, E., d'Abreu, M.C., Ferraz-de-Oliveira, M.I. (2015) Overgrazing in the Montado? The need for monitoring grazing pressure at paddock scale. *Agroforestry Systems* 90, 57-68.

Schumacher, S., Bugmann, H., Mladenoff, D.J. (2004) Improving the formulation of tree growth and succession in a spatially explicit landscape model. *Ecological Modelling* 180, 175-194.

Schumacher, S., Reineking, B., Sibold, J., Bugmann, H. (2006) Modelling the impact of climate and vegetation on fire regimes in mountain landscapes. *Landscape Ecology* 21, 539–554

Second National Climate Change Strategy [Második Nemzeti Éghajlatváltozási Stratégia] (2017) Budapest, Hungary: Ministry of National Development.

Shao G.F., Bugmann, H., Yan, X.D. (2001) A comparative analysis of the structure and behaviour of three gap models at sites in northeastern China. *Climatic Change* 51, 389–413.

Madsen, M.S., Maule, C.F., Christensen, J.H., Fronzek, S. & Carter, T.R. (2016). IMPRESSIONS Climate Scenarios. EU FP7 IMPRESSIONS Project Deliverable D2.3. Available from www.impressions-project.eu

Snell, R.S., Peringer, A., Bugmann, H. (2017) Integrating processes across temporal and spatial scales to simulate landscape patterns and dynamics in mountain pasture-woodlands. *Landscape Ecology* 32, 1079–1096. [doi:10.1007/s10980-017-0511-1]

Stagl, J., Hattermann, F. (2015) Impacts of Climate Change on the Hydrological Regime of the Danube River and Its Tributaries Using an Ensemble of Climate Scenarios. *Water* 7, 6139–6172. [doi:10.3390/w7116139]

Temperli, C., Bugmann, H., Elkin, C. (2012) Adaptive management for competing forest goods and services under climate change. *Ecological Applications* 22, 2065–2077

Vardoulakis, S., Dear, K., Hajat, S., Heaviside, C., Eggen, B., McMichael, A.J. (2014) Comparative assessment of the effects of climate change on heat- and cold-related mortality in the United Kingdom and Australia. *Environmental Health Perspectives* 122, 1285–1292. [doi: 10.1289/ehp.1307524]

Weedon, G. P., Balsamo G., Bellouin, N., Gomes, S., Best, M. J., Viterbo, P. (2014) The WFDEI meteorological forcing data : WATCH Forcing Data and its use to assess global and regional reference crop evaporation over land during the twentieth century, *Journal of Hydrometeorology* 12, 823–848 [doi:10.1002/2014WRO15638]

Wimmer, F., Audsley, E., Malsy, M., Savin, C., Dunford, R., Harrison, P., Schaldach, R., Flörke, M. (2015) Modelling the effects of cross-sectoral water allocation schemes in Europe. *Climatic Change* 128, 229–244.

Zellmer, K., Gramberger, M., Haenen, S. (2015) Report on first set of stakeholder workshops. EU FP7 IMPRESSIONS Project Deliverable D6A.2 [Restricted access].