UNIVERSITY OF SOUTHAMPTON

FACULTY OF ENGINEERING AND THE ENVIRONMENT

Civil, Maritime and Environmental Engineering and Science

The Food-Water-Land-Ecosystems Nexus in Europe: An Integrated Assessment

by

Abiy S. Kebede

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ABSTRACT

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ABSTRACT

Climate and socio-economic change impacts interact in complex ways. These are likely to cross traditional sectoral and regional boundaries with cascading indirect and potentially far reaching repercussions. This is particularly important for the food-water-land-ecosystems (FWLE) nexus. A holistic understanding of these interactions is central for devising appropriate adaptation strategies. This thesis presents a systematic methodological framework that provides new insights into understanding key sensitivities and uncertainties of these possible cross-sectoral impacts for informing future adaptation policies. The research is based on: (1) appraisal of integrated assessment models (IAMs), and (2) investigation of the direct and indirect implications of a wide range of climate and socio-economic scenarios taking into account important cross-sectoral linkages and interactions between six key European land- and water-based sectors/sub-systems (*agriculture*, *biodiversity*, *coasts*, *forests*, *urban*, and *water*). This is achieved through (1) a review of existing integrated approaches and tools, and (2) assessment and extensive application of one European IAM – the CLIMSAVE[1] Integrated Assessment Platform (IAP). The IAP application uses a combined approach drawing on a systematic: (i) Sensitivity analysis based on a One-Driver-at-a-Time (ODAT) approach, (ii) Scenario and uncertainty analysis based on Multiple-Drivers-at-a-Time (MDAT) approach, and (iii) Robustness Assessment of Adaptation Policies (RAAP). The key outputs include: (i) new quantitative insights into the complex interactions of the FWLE nexus and associated synergies, conflicts and trade-offs in Europe, (ii) identifying key sensitivities and uncertainties of the potential cross-sectoral impacts and adaptation policies under various scenarios of future changes in climate as well as social, technological, economic, environmental, and policy governance settings, (iii) development of a new nexus-based conceptual framework for a long-term, multi- and cross-sectoral adaptation planning, and (iv) identification of potential areas of improvement of the IAP to inform development of the next generation of IAMs to assess the FWLE nexus.

The ODAT analysis demonstrates that while a large number of drivers (20 out of 25) affect most sectors/sub-systems either directly or indirectly, eight drivers are key parameters at the European scale, with important cross-sectoral implications (i.e., ‘strong’ and ‘non-linear’ impacts on more than one sector/sub-system). These include: four climatic (temperature, summer and winter precipitation, and CO_2 concentration) and four socio-economic (population, GDP, food imports, and agricultural yields) factors. Considering a wide range of scenario combinations of these drivers (taking into account the ‘full’ and ‘plausible sample’ scenario ranges), the MDAT analysis demonstrates that: (i) food production is likely to be the main driver of Europe’s future landscape change dynamics (even without climate change), (ii) agriculture and land use allocation in general is often driven by complex interactions between various sectors/sub-systems, (iii) there are no clear trends/patterns in future food production under most climate scenarios, (iv) agricultural changes have significant cascading effects on other sectors/sub-systems such as forestry, biodiversity, and water and (v) there are consistent trends for biodiversity, water and flood impacts with regional variations. The results also demonstrate that the combined effects of socio-economic and climatic factors are not always additive, highlighting the complexity of understanding impacts across sectors/sub-systems and regions. As a result, adaptation policy choices are complicated and difficult, even without climate change. A better understanding of the critical trade-offs across sectors/sub-systems and regions under various adaptation options is required. Such systematic analysis provides important insights for decision-makers to devise robust adaptation policies that maximise benefits and minimise unintended consequences across sectors/sub-systems and scales.

[1] CLIMSAVE (Climate change integrated assessment methodology for cross-sectoral adaptation and vulnerability in Europe) is an FP7 project (2010–2013) funded by the European Commission. The CLIMSAVE IAP is an interactive exploratory web-based integrated landscape change assessment model that allows stakeholders to investigate climate and socio-economic change impacts, adaptation and vulnerabilities for six key sectors/sub-systems (*agriculture, biodiversity, coasts, forests, urban areas and water resources*) (Harrison *et al*. 2013; 2015a).

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DECLARATION OF AUTHORSHIP

I, Abiy S. Kebede, declare that this thesis and the work presented in it are my own and have been generated by me as the result of my own original research.

Thesis Title: 'The Food-Water-Land-Ecosystems Nexus in Europe: An Integrated Assessment'

I confirm that:

1. This work was done wholly or mainly while in candidature for a research degree at this University;
2. Where any part of this thesis has previously been submitted for a degree or any other qualification at this University or any other institution, this has been clearly stated;
3. Where I have consulted the published work of others, this is always clearly attributed;
4. Where I have quoted from the work of others, the source is always given. With the exception of such quotations, this thesis is entirely my own work;
5. I have acknowledged all main sources of help;
6. Where the thesis is based on work done by myself jointly with others, I have made clear exactly what was done by others and what I have contributed myself;
7. Parts of this work have been published as detailed below (also see Appendix D):

Peer-Reviewed Journal Papers:

Kebede AS, Dunford R, Mokrech M, Audsley E, Harrison PA, Holman IP, Nicholls RJ, Rickebusch S, Rounsevell MDA, Sabate S, Sallaba F, Sanchez A, Savin C-M, Trnka M, Wimmer F (2015) Direct and indirect impacts of climate and socio-economic change in Europe: A sensitivity analysis for key land- and water-based sectors. *Climatic Change*, 128(3-4):261–277.

Mokrech M, **Kebede AS**, Nicholls RJ, 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(3-4):245–260.

Harrison PA, Dunford R, Savin C, Rounsevell MDA, Holman IP, **Kebede AS**, Stuch B (2015) Cross-sectoral impacts of climate change and socio-economic change for multiple, European land- and water-based sectors. *Climatic Change*, 128(3-4):279–292.

Book Chapters:

Mokrech M, **Kebede AS**, Nicholls RJ (2016) Assessing flood impacts, wetland changes and adaptation in Europe: the CLIMSAVE approach. *In*: Gray *et al*. (eds.), *Participatory modelling for adaptation: Theory, methods, and applications*. Springer Publishing, New York City (*in press*).

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Signed: ……………………………………………………………………

Date: ……………………………………………………………………..….

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ABBREVIATIONS

ABM	*Agent Based Models*
ACACIA	*A Concerted Action towards a comprehensive Climate Impacts and Adaptations assessment for the European Union*
ACCELERATES	*Assessing Climate Change Effects on Land use and Ecosystems: from Regional Analysis to the European Scale*
AIM	*The Asia-Pacific Integrated Model*
ANNs	*Artificial Neural Networks*
AS	*Artificial Surfaces*
BN	*Bayesian Networks*
BVI	*Biodiversity Vulnerability Index*
ClimAID	*Integrated Assessment for Effective Climate Change Adaptation Strategies in New York State*
CLIMPACTS system	*An integrated model for assessment of the effects of climate change on the New Zealand environment*
CLIMSAVE	*CLimate change Integrated assessment Methodology for cross-Sectoral Adaptation and Vulnerability in Europe (EU FP7 project)*
DINAS-COAST	*Dynamic and Interactive Assessment of National, Regional and Global Vulnerability of Coastal Zones to Climate Change and Sea-Level Rise (EU FP5 project)*
DIVA	*Dynamic Interactive Vulnerability Assessment*
ERMITAGE	*Enhancing Robustness and Model Integration for The Assessment of Global Environmental Change (EU FP7 project)*
FP	*Food Production*
FWLE	*Food-Water-Land-Ecosystems nexus*
GENIE-I	*Grid ENabled Integrated Earth system Model*
GHGs	*Greenhouse Gases*
GIS	*Geographical Information System*
HELIX	*High-End cLimate Impacts and eXtremes (EU FP7 project)*
IA	*Integrated Assessment*
IAMs	*Integrated Assessment Models*
IAP	*Integrated Assessment Platform*
IMPRESSIONS	*Impacts and Risks from High-end Scenarios: Strategies for Innovative Solutions (EU FP7 project)*
IPCC	*Intergovernmental Panel on Climate Change*
ISI-MIP	*Inter-Sectoral Impact Model Intercomparison Project*
KBM	*Knowledge-Based Models*
LUD	*Land Use Diversity*
MEDIATION	*Methodology for Effective Decision-making on Impacts and AdaptaTION (EU FP7 project)*
PESETA	*Projection of Economic impacts of climate change in Sectors of the European Union based on botTom-up Analysis (EU FP7 project)*
PF100	*People Flooded by a 1 in 100 year event*
PRIMA	*Platform for Regional Integrated Modeling and Analysis*
RegIS	*Regional Impact Simulator*
RISES-AM	*Responses to coastal climate change: Innovative Strategies for high End Scenarios – Adaptation and Mitigation (EU FP7 project)*

RESPONSES	*European Responses to Climate Change (EU FP7 project)*
SimCLIM	*A software modelling system for simulating bio-physical and socio-economic effects of climate variability and change*
SD	*Systems Dynamics*
TaiCCAT	*Taiwan integrated research program on Climate Change Adaptation Technology*
TP	*Timber Production*
WEI	*Water Exploitation Index*

1. INTRODUCTION

1.1 Background

Climate change is projected to impact human and natural systems worldwide. These impacts are likely to cross traditional sectoral and regional boundaries, where impacts in one sector/sub-system[2] or region may affect the capacity to respond of other sectors/sub-systems or regions. This can be particularly important when considering the food-water-land-ecosystems (FWLE) nexus interactions and associated synergies, conflicts and trade-offs across scales under changing conditions. A comprehensive understanding of these complex interactions provides important information for decision-makers to better understand the full extent of uncertainties of impacts and vulnerabilities (Harrison *et al*. 2015a). Such insights are essential for developing appropriate adaptation as well as mitigation strategies[3] (Kraucunas *et al*. 2013). Integrated assessment (IA)[4] methods provide a consistent framework for understanding the linkages/interactions and feedbacks between different sectors/sub-systems across scales for a wide range of drivers, including climate change. They play a significant role in providing important scientific insights into the complex planning and policy challenges surrounding climate change adaptation (Holman *et al*. 2005a,b; Harrison *et al*. 2013). In particular, this facilitates robust decision-making for designing cross-sectoral adaptation (e.g., Harremoes and Turner 2001; Lempert *et al*. 2006). For example, a holistic understanding of the complex interactions allows decision-makers to formulate adaptation policies, which maximise benefits and minimise unintended consequences across sectors/sub-systems and regions.

A number of different assessment models and tools have been developed and applied for investigating climate change impacts and adaptation for different sectors/sub-systems and at different scales. Examples of such studies include: agriculture (global: Fischer *et al*. 2005; European: Wolf and Van Oijen 2003), biodiversity (global: Parmesan and Yohe 2003; European:

[2] The term 'sectors/sub-systems' is used in this thesis in order to: (i) maintain consistency with the use of the term 'sector' within the CLIMSAVE project, which this PhD is part of, as well as (ii) reflect the use of the term as components/sub-systems of some larger 'whole' system. Hence, the combined term here refers to components of a larger system, which is framed in this thesis as the 'Food-Water-Land-Ecosystems nexus', focusing on the land- and water-based components/sub-systems related to aspects of the human settlement and socio-economic activities (e.g., urban areas, agriculture, forestry, coastal systems, etc.) and the natural and managed resources and their uses (e.g., land and water resources) and associated ecosystems (e.g., biodiversity).

[3] 'Adaptation' is often referred as responses to climate change only, as defined by IPCC (2001) as "*…adjustments in ecological, social, or economic systems in response to actual or expected climatic stimuli and their effects or impacts.*" (p.879). However, in this thesis it refers more broadly to response measures to reduce negative effects of and maximise benefits from all kinds of risks/ changes associated with both climatic and non-climatic drivers. On the other hand, 'mitigation' refers to those global-scale efforts linked to climate policy to reduce greenhouse gas (GHG) emissions and increase sinks, minimizing climate change.

[4] Defined as "*…an interdisciplinary process that combines, interprets, and communicates knowledge from diverse scientific disciplines from the natural and social sciences to investigate and understand causal relationships within and between complicated systems*" (IPCC 2001, p.25).

Harrison *et al*. 2006), flooding (global: Nicholls 2004; European: Hinkel *et al*. 2010), forestry (global: Perez-Garcia et al. 2002; European: Nabuurs *et al*. 2002), and water (global: Arnell 2004; European: Lehner *et al*. 2006). Such models usually treat each sector/sub-system independently and to-date most climate change impact assessments still focus on sector-based analysis (Harrison *et al*. 2016; Holman *et al*. 2008a,b). There are few exceptions, which mainly focus on two closely related sectors/sub-systems (e.g., agriculture and water; Falloon and Betts 2010), with even fewer analysing three or more sectors/sub-systems (Liu *et al*. 2015). Such approaches ignore important cross-sectoral interactions and feedbacks (Harrison *et al*. 2015a) that characterise a sustainable functioning of various socio-economic and ecological systems at different scales (e.g., Isard *et al*. 1968; Baustian *et al*. 2014). Hence, a truly systematic view is missing and important interdependencies between interacting sectors/sub-systems are still poorly understood (Hall *et al*. 2013; Frieler and the ISI-MIP Team 2013). Due to the lack of consistent quantification of the extent and magnitude of such impacts across sectors/sub-systems and regions, there is a challenge in integrated adaptation planning. Moreover, understanding such cross-sectoral interactions is important as changes in one sector/sub-system can affect another sector/sub-system either directly (e.g., the effect of land use change on biodiversity), or indirectly through policy changes (e.g., effects of coastal flood defence measures on coastal habitats) (Lee 2001; Holman *et al*. 2008a,b; Harrison *et al*. 2015a). Ignoring or having a limited understanding of such interdependencies could lead to potential under- or over-estimation of future impacts, and hence adaptation needs across sectors/sub-systems and scales (Carter *et al*. 2007).

Moreover, the impacts due to climate change are in addition to those associated with the continuing and increasing pressures from changing demographics, economies, technologies, lifestyles and policies (Moss *et al*. 2010). In addition, climate and socio-economic change impacts interact in potentially complex, and non-additive ways (Harrison *et al*. 2015a). However, most impact assessment studies have a particular emphasis on the implications of climate drivers only[5] (Holman *et al*. 2008a,b). The combined and additional effects of non-climatic drivers have been given little attention (Berkhout *et al*. 2002), and when considered they are treated either independently or rigidly combined with climate scenarios (Holman *et al*. 2005a,b). In addition, inconsistent scenario set-ups across sectors/sub-systems and scales often impede even meaningful comparison and aggregation of existing studies.

[5] Note that this study focusses mainly on IAMs used for assessing climate change impacts and adaptation (see Figure 2.1). Other energy-related IAMs (e.g., for assessing climate mitigation policies) often have more detailed representation of socio-economic factors (than, for example, natural dynamics). However, even for those IAMs, a comprehensive sensitivity analysis of the socio-economic factors as drivers is still relatively limited (e.g., Anderson *et al*. 2012).

Consequently, these limitations in current impact assessment methods present important challenges in planning appropriate cross-sectoral adaptation strategies. This highlights the need for structured approaches for a better understanding of future cross-sectoral impacts (Harrison *et al*. 2013). An understanding of cross-sectoral interactions and feedbacks and associated direct/indirect implications of future climatic and socio-economic changes will allow identification of the most sensitive and vulnerable sectors/sub-systems and regions. Such information will help stakeholders and decision-makers to set sectoral and regional priorities for robust integrated adaptation responses (Fankhauser and Soare 2012). However, lack of such knowledge in planning future adaptation policies still remains a challenge.

1.2 Problem Statement

Due to the cross-boundary nature of climate change, impacts occurring in one sector/sub-system or region are not likely to be confined to that particular sector/sub-system or region. This leads to the potential for cascading indirect and associated secondary effects across different sectors/sub-systems and/or regions (Nicholls and Kebede 2012; World Bank 2013). Hence, stakeholders and decision-makers are facing important challenges in designing appropriate adaptation and/or mitigation policies (e.g., Mercure *et al*. 2015). A comprehensive understanding of the potential impacts of future changes is considered critical to identifying the need for appropriate adaptation planning (PROVIA 2013a). Hence, climate change impact assessments and robust adaptation planning require a systematic integrated assessment of cross-sectoral impacts by taking into account: (i) the combined effects of both climatic and non-climatic factors (Berkhout *et al*. 2002), and (ii) the interdependencies and associated synergies, conflicts and trade-offs between different sectors/sub-systems and regions (Harrison *et al*. 2013). IAMs for climate policy analysis are often criticised due to their complexity and lack of transparency (e.g., Pindyck 2015) and their “highly restrictive assumptions” on climate catastrophes and societal risk aversion (e.g., Kaufman 2012). However, IAMs have provided crucial new insights to the climate policy debate especially, “regarding the evaluation of policies and responses, structuring knowledge, and prioritizing uncertainties … have also contributed to the basic knowledge about the climate systems as a whole” (Markandya *et al*. 2001; p.490). In addition, recent advances in IAMs for impacts and adaptation assessments play a key role in providing a holistic and consistent framework and important insights that can complement existing detailed sector-specific assessments and methods. Such IAMs integrate knowledge across relevant disciplines and methods and provide a better understanding of important systems inter-linkages and feedbacks. This has the potential to organise and deliver policy-relevant information suitable for improved decision-making (Harremoes and Turner 2001).

However, there are relatively few studies that integrate impact assessment models across a wide range of sectors/sub-systems (Harrison *et al*. 2015a). Some examples on previous cross-sectoral integrated (qualitatively/quantitatively) assessment studies include: agriculture and biodiversity (Berry *et al*. 2006; Rounsevell *et al*. 2006); water and agriculture (Xiong *et al*. 2010; Barthel *et al*. 2012); multiple urban infrastructure types (Kirchen *et al*. 2008; Hall *et al*. 2013; Otto *et al*. 2015); and surface and ground water resources (Baruffi *et al*. 2012). There are even fewer studies that integrate across several (e.g., more than three/four) sectors/sub-systems and consider the combined effects of both climate and socio-economic change drivers, and adaptation (Holman *et al*. 2008a,b; Harrison *et al*. 2013). Moreover, despite the rapid growth of the development and use of IAMs across a range of disciplines, scales and complexities (e.g., Kenny *et al*. 2001; Matsuoka *et al*. 2001; Holman *et al*. 2005a,b), their quantitative application in the context of informing adaptation policies and supporting the decision-making process remains a challenge (e.g., Schneider and Lane 2005), where there is limited experience. Hence, there are a series of key questions:

(1) What are the roles of IAMs in understanding important nexus interactions and feedbacks and informing cross-sectoral adaptation policy design?

(2) What are the potential cross-sectoral impacts and associated uncertainties under a range of future climate and socio-economic change scenarios?

(3) Are there non-linearities and thresholds in these cross-sectoral impacts?

(4) How do the human-nature systems interactions influence future adaptation policy options?

(5) How can such knowledge inform the design of robust adaptation policies?

Uncertainty poses particular challenges to IA modelling approaches as they attempt to capture complex interactions between different dimensions of a given problem (e.g., Rotmans and van Asselt 2001). Integrated assessment of climate change also faces such challenge, for example, in terms of quantifying potential error propagation within integrated modelling frameworks (see Brown *et al*. 2015; Dunford *et al*. 2015). For example, as part of the CLIMSAVE project Dunford *et al*. (2015) identified two main sources of uncertainty surrounding integrated assessment modelling approaches that are also relevant to the CLIMSAVE IAP, namely: (i) scenario uncertainty (e.g., associated with future climate and socio-economic change uncertainties), and (ii) model uncertainty (e.g., data uncertainty, model incompleteness, accumulated uncertainty due to the integrated modelling chain), which are further discussed in Chapter 6. Different integrated assessment studies have used various approaches for uncertainty analysis. Some examples of commonly used approaches include: Sensitivity analysis, scenario analysis, Monte Carlo analysis, multiple model simulation, etc. (e.g., Kann and Weyant 2000; Resfsgaard *et al*. 2007). Applicability of these methods varies depending on, among others, the level of complexity of the system being modelled and the IAMs themselves and their flexibility. Hence, the choice of appropriate method(s) and management of uncertainty and error propagation in IAMs is crucial (e.g., van der Sluijs 1996; Messina *et al*. 2008). Scenario analysis has become an important tool for dealing with uncertainties particularly when dealing with complex problems and uncertain systems (e.g., Swart *et al*. 2004). However, existing climate change impact assessment and adaptation planning studies typically use a limited (usually four) number of future scenarios (Carter *et al*. 2001; Berkhout *et al*. 2002). Such approaches may not capture the full spectrum of uncertainties, and hence may miss out potential 'surprises'. In addition, rigidly-combined (climate and/or socio-economic change) scenario approaches also make it difficult to: (i) compare effects of individual drivers considered within the scenarios, and (ii) identify which parameters or assumptions are most important in planning future cross-sectoral adaptation priorities.

This thesis develops a systematic methodological framework based on a combined approach drawing on a systematic sensitivity, scenario, and robustness analysis. The method is applied to investigate key sensitivities and uncertainties of the potential impacts and adaptation policies across multiple sectors/sub-systems (i.e., the FWLE nexus) in Europe considering several (i.e., thousands) scenarios of future changes in climate as well as socio-economic factors. The research is part of the European Commission FP7 CLIMSAVE[6] project, which developed an interactive web-based IA tool, the CLIMSAVE Integrated Assessment Platform (IAP). The thesis focusses on appraisal of IAMs based on: (i) a review of existing IA tools and modelling approaches, and (ii) an extensive assessment and application of the CLIMSAVE IAP. The study examines the role of IAMs in understanding important cross-sectoral linkages/interactions and informing future adaptation policies under uncertain future climate and socio-economic conditions.

1.3 Aims and Objectives

The overall aim of the research is to provide improved understanding of the food-water-land-ecosystems (FWLE) nexus in Europe, including the associated sensitivities and uncertainties of the potential cross-sectoral impacts and adaptation policies under changing conditions. In this context, a wide range of scenarios of future changes in climate as well as social, economic,

[6] CLimate change Integrated assessment Methodology for cross-Sectoral Adaptation and Vulnerability in Europe: www.climsave.eu. The IAP is an integrated assessment model, which can be run on the freely available web-based interface, or in batch mode (as used in this research). Detailed description of the CLIMSAVE integrated methodology and the IAP is presented in Chapter 3.

technological, environmental, and policy governance scenario settings are explored. The research uses a combined approach to investigate the direct and indirect implications of the various scenarios taking into account important cross-sectoral linkages/interactions between six key European land- and water-based sectors/sub-systems (agriculture, biodiversity, coasts, forests, urban and water) and assess robustness of different adaptation policies. Such analysis provides better quantification and increased understanding of the complex relationships between input and output variables in a system of integrated models. Hence, the study aims towards providing a better understanding of the interdependencies and associated synergies, conflicts and trade-offs between the various sectors/sub-systems and potential adaptation strategies in Europe. In order to achieve this aim, the following objectives are set out as the key stages of the research methodological framework:

(1) Appraisal of IAMs based on a review of existing IA modelling approaches and tools and assessment and application of one European IAM – the CLIMSAVE IAP. This aims to set the IAP in a broader context and identify potential areas of improvement of the IAP to inform development of the next generation of IAMs.

(2) A systematic sensitivity analysis based on a One-Driver-At-a-Time (ODAT) approach. This analysis aims to identify: (i) those sectors/sub-systems and regions most sensitive to future changes, (ii) the mechanisms and directions of sensitivity (direct/indirect and positive/negative), (iii) the form and magnitudes of sensitivity (linear/non-linear and insignificant/weak/strong), and (iv) the relative importance of the various key climatic and socio-economic drivers across sectors/sub-systems and regions. The ODAT analysis results will also be used as a screening to select the most important climate and socio-economic drivers that have important cross-sectoral implications, with significant impacts and non-linear amplifications on more than one sector/sub-system. These drivers will then be used to develop several (thousands) scenario combinations that characterise future changes in multiple drivers that cover wide ranges of future climate and/or socio-economic change scenario uncertainties.

(3) A scenario and uncertainty analysis using a Multiple-Drivers-At-a-Time (MDAT) approach. This will assess the extent of the sensitivity and uncertainties of cross-sectoral impacts of both climate and socio-economic change and hence future adaptation needs. The MDAT assessment considers three classes of scenario groups: (i) *climate change only (CD)*, (ii) *socio-economic change only (SED)*, and (iii) *combined climate and socio-economic change (C&SED) scenarios*. This will provide a better understanding of the sensitivity of impacts and comparison of the relative importance of the drivers and scenario classes and

associated contribution to the overall uncertainty of future cross-sectoral impacts and adaptation needs. The analysis has three key focuses to assess changes in terms of: (i) statistical significance, (ii) key sensitivities and uncertainties, and (ii) spatial patterns of future FWLE nexus interactions and associated impacts across sectors/sub-systems, regions, and scenarios.

(4) A robustness assessment of adaptation policies (RAAP). This analysis will provide improved understanding of critical cross-sectoral synergies, conflicts, and trade-offs between different adaptation policies across sectors/sub-systems, scales and scenarios. The analysis aims to identify robust cross-sectoral adaptation policies in Europe to better adapt and reduce broad-scale impacts across sectors/sub-systems, regions and scenarios under a range of uncertainties. The three key steps of the analysis include: (i) identification of appropriate sets of cross-sectoral adaptation strategies, (ii) evaluation of cross-sectoral impacts before (i.e., potential impacts) and after (i.e., residual impacts) adaptation, and (iii) assessment of robustness of the various adaptation policy options.

The expected research outputs include:

(1) Improved insights on understanding of the interdependencies and associated synergies, conflicts, and trade-offs between the FWLE nexus systems, including identification of potential indirect and non-linear amplifications of impacts across sectors/sub-systems and regions in Europe.

(2) Identification of robust adaptation policies at the scale of Europe.

(3) A new nexus-based conceptual framework for long-term and multi-/cross-sectoral adaptation planning.

(4) A structured and enhanced communication of IAM applications to decision-makers in terms of selecting appropriate IA methods and tools.

(5) Identification of potential areas of attention and future directions for uncertainty reduction to inform development of the next generation of IAMs for improved multi-sector/sub-system, multi-model, multi-scale and multi-scenario based analysis of future impacts of and adaptation to climate and socio-economic changes, without losing important sectoral details.

1.4 Thesis Structure

Chapter 1: INTRODUCTION: Provides a general background about the context of the thesis and identifies the research problems, defines the aims and objectives, and presents the expected research outputs.

Chapter 2: LITERATURE REVIEW: Presents a review of the literature on climate and socio-economic change sectoral impacts and adaptation, the existing assessment methods and tools, the cross-sectoral nature of impacts and adaptation needs and associated integrated approaches. Existing climate change impacts and adaptation IAMs are described, with a particular focus on regional/continental scale landscape change modelling applications. It identifies and compares the strengths and limitations of existing IAMs and sets the CLIMSAVE IAP in a broader context to identify potential areas of improvement of the IAP to inform future IAM developments. Finally, it highlights the need for a nexus approach in future adaptation planning and how this facilitates in designing of robust adaptation policies.

Chapter 3: THE CLIMSAVE INTEGRATED APPROACH: A EUROPEAN ANALYSIS: Introduces the CLIMSAVE integrated methodological framework with the cross-sectoral focus approach. It presents a detailed description of the CLIMSAVE IAP, including how it advances the current knowledge in IA modelling applications on a regional scale impacts and adaptation assessment. Finally, a summary of the research gap, overview of the research objectives and how this research aims to fill this gap are presented.

Chapter 4: MATERIALS AND METHODOLOGY: Presents a description of the research materials and methodological framework, including the study area and scale of analysis, the selected impact indicators, and the methods used at the three key stages of the research: (a) The ODAT sensitivity analysis, (2) The MDAT scenario and uncertainty analysis, and (3) The robustness assessment of adaptation policies (RAAP).

Chapter 5: RESULTS AND DISCUSSION (PART I): THE ONE-DRIVER-AT-A-TIME SENSITIVITY ANALYSIS: Presents the results with a detailed interpretation and discussion of the key outputs of the ODAT sensitivity analysis, and outlines how this feeds into the MDAT analysis.

Chapter 6: RESULTS AND DISCUSSION (PART II): THE MULTIPLE-DRIVERS-AT-A-TIME SCENARIO AND UNCERTAINTY ANALYSIS: Presents the results with a detailed interpretation and discussion of the key outputs of the MDAT scenario and uncertainty analysis approach, and outlines how this combined with the ODAT analysis results are used in the RAAP analysis.

Chapter 7: THE ROLE OF IAMs IN UNDESTANDING THE FOOD-WATER-LAND-ECOSYSTEMS NEXUS: Discusses the key sensitivities and uncertainties of future cross-sectoral impacts (based on the ODAT and MDAT analyses results) and presents and discusses the robustness of different adaptation policies in reducing these impacts across sectors/sub-systems, scales and scenarios. It also identifies and discusses the key insights of the research. This includes how such analysis can be used in practice, highlighting the key roles of IAMs in long-term adaptation planning and the associated benefits and challenges, presenting a new nexus-based conceptual framework for planning long-term, multi-/cross-sectoral adaptation, and how the CLIMSAVE IA approach can be improved and how that can inform the development of the next generation of IAMs.

Chapter 8: SUMMARY, CONCLUSIONS AND RECOMMENDATIONS: This chapter draws the key messages and conclusions identified in terms of achieving the aims and objectives of the research, and outlines the key recommendations for future research in terms of both improving the CLIMSAVE IA approach as well as informing future development of the next generation of IAMs for assessing the FWLE nexus.

APPENDICES: Presents a summary of all additional materials relevant to the contents of the thesis that are referenced in the main text. It also includes publications (full papers/abstracts) co-/authored from the research work, including peer-reviewed journal papers, book chapters, conference papers, and project reports.

REFERENCES: Lists all the references cited throughout the research thesis.

2. LITERATURE REVIEW

This chapter provides background information for the research based on a review of the literature on: climate and socio-economic change impacts and adaptation for key sectors/sub-systems in Europe (Section 2.1), impacts and adaptation assessment methods and tools (Section 2.2), the role of systems integration approaches in understanding cross-sectoral impacts and adaptation (Section 2.3), appraisal of existing IA modelling approaches and frameworks based on identifying key strengths and limitations (Section 2.4), and highlights the need for a nexus approach in future adaptation planning and how systems integration approaches facilitate the decision-making process in designing robust adaptation policies (Section 2.5). In doing so, the review provides an overview of the context required to understand this research and highlights the research gap that the thesis aims to address.

2.1 Climate and Socio-Economic Change Impacts and Adaptation in Europe

There is growing and strong consensus that the climate is changing and considerable scientific evidence shows that it is linked to human-induced emissions of heat-trapping greenhouse gases (GHGs)[7] (IPCC 2013). The long-term trends of the changing climate accumulate over time and are expected to intensify through the 21st century (IPCC 2013). These changes are likely to have profound impacts and cost implications for the social, political, economic and environmental sustainability and well-being of human societies and health of natural ecosystems worldwide (IPCC 2007; 2014). Hence, the problem of climate change, which encompasses all aspects of environmental science and economics, remains as one of the most important environmental and scientific challenges that will be faced in the coming decades. Managing this global environmental challenge is complicated by the problem of an ‘uncertain future’. The future of the climate system is uncertain and dynamic in itself: however, the direction of travel of many key environmental parameters will also be driven by socio-economics and reflect decisions based on social, ethical, political and institutional factors that are even more difficult to predict and model. Hence, the control of this global environmental problem remains as a formidable challenge that requires a strong coordination among countries for implementation and enforcement of credible control policies across countries (Kelly and Kolstad 1998). Such co-operations require reliable and comprehensive science-based information for policy and decision-making on adaptation as well as mitigation responses at different scales, ranging from local to global levels.

[7] Such as carbon dioxide (CO_2), nitrous Oxide (N_2O), methane (CH_4), etc.

Some of the anticipated changes in climate include: rising temperatures, variation in precipitation, frequent and severe extreme weather events and shifting seasons, accelerated sea-level rise, and stronger and more frequent storms (IPCC 2013). For example, some of the potential impacts of such environmental changes in Europe include: (1) a decline in agricultural productivity in some regions that threatens food security (e.g., Audsley *et al.* 2006; Aydinalp and Cresser 2008; Iglesias *et al.* 2009; Nelson *et al.* 2009); (2) shifts in species distribution and composition of habitats and ecosystems that characterise landscapes (e.g., Green *et al.* 2003; Brooker and Young 2005; Berry *et al*. 2006); (3) increasing risk of flooding for people and properties and associated damage and costs (e.g., Costa *et al.* 2009; Richards and Nicholls 2009; Hinkel *et al*. 2010; Brown *et al.* 2011; Feyen and Watkiss 2011); (4) increased risk of wild fire and adverse effects of prolonged drought on forest growth and wood production (e.g., Ciais *et al.* 2005; Moriondo *et al.* 2006; Lindner *et al.* 2010); (5) impacts on hydrological processes and regimes, and associated effects on the availability, quality, and use of water resources (e.g., EEA 2007; Bates *et al.* 2008). The extent and magnitude of these potential impacts varies: (1) over time, (2) across regions, ecosystems, and sectors/sub-systems, and (3) with the ability of these regions, ecosystems, and sectors/sub-systems to adapt to, and/or cope with, these changes. Nevertheless, such consequences pose significant threats to all sectors/sub-systems of society and the environment at all scales, ranging from local to global (spatial) and short- to long-term (temporal) scales. Moreover, these climate impacts are in addition to the continuing and increasing pressures from the social and human demographic, economic, political, lifestyle, policy and technological changes (Moss *et al*. 2010). This highlights the importance of accounting for socio-economic change and climate change drivers in a co-evolutionary way (Lorenzoni *et al*. 2000).

Europe is projected to experience regionally varying changes in temperature and rainfall (IPCC 2014; Jacob *et al*. 2014). The annual average temperature is projected to increase throughout Europe (IPCC 2014). The largest warming is projected in Southern Europe in summer and in Northern and Eastern Europe in winter. The mean annual precipitation is also projected to increase in Northern Europe and decrease in Southern Europe, while there are no clear trends in Continental Europe (IPCC 2014). These projections also show seasonal variations, with a decrease in the summer and increase in winter, with mountainous areas projected with more rain than snow. The climate projections also show that there will be a marked increase in the extremes, such as in high temperature, heavy precipitation events and meteorological droughts with regional variations across Europe. Further, global mean sea levels are projected to rise between 0.29–0.82m for 2081-2100 (compared to 1986-2005) with regional variations.

In addition, non-climate drivers and associated future trends including demographic change and socio-economic development (e.g., de Mooij and Tang 2003; Davoudi *et al*. 2010), land use change (e.g., Letourneau *et al*. 2012) and European policy (e.g., Helming *et al*. 2011) play an important role in future impacts and adaptation needs. Hence, these changes in climate and socio-economic drivers and policy are likely to have significant impacts on a wide range of sectors/sub-systems and regions over the coming few decades (IPCC 2014).

The literature on climate change has identified a number of sectors/sub-systems that are and could be directly affected by a changing climate (Table 2.1). Various studies also demonstrated the challenge that policy-makers are faced with in incorporating climate adaptation into planning processes as a necessary strategy for sustainable long-term development across these sectors/sub-systems. Table 2.1 presents a list of these sectors/sub-systems with the main climate and related drivers of change and some example references.

Table 2.1: *Lists of sectors/sub-systems that are and could be affected by climate change*.

Sectors/sub-systems	**Main climate and related drivers of change**	**Example References**
Agriculture	Temperature, precipitation, atmospheric CO_2 & O_3 conc., sea-level rise (in coastal agricultural areas), extreme events (e.g., floods, hurricanes, heat waves, severe droughts)	Hitz and Smith 2004; Iglesias *et al*. 2009; Lavalle *et al*. 2009; Arnell *et al*. 2014; Piontek *et al*. 2014; Rosenzweig *et al*. 2014
Biodiversity and ecosystems	Temperature, precipitation, atmospheric CO_2 conc., sea-level rise (coastal habitats), extreme events (e.g., floods, heat waves, severe droughts)	Sala *et al*. 2000; Brooker and Young 2005; Berry *et al*. 2006; Harrison *et al*. 2006; Arnell *et al*. 2014; Piontek *et al*. 2014
Coastal systems and low-lying areas	Sea-level rise, severe storms, extreme sea levels, winds, waves, ocean acidification, freshwater inputs, temperature and precipitation changes	Richards and Nicholls 2009; Hinkel *et al*. 2010; Brown *et al*. 2011; Ciscar *et al*. 2011; Arnell *et al*. 2014; Joshi *et al*. 2015
Energy	Temperature (for thermal power plants), precipitation (for hydropower), wind speed (for wind powers), weather patterns (for solar powers)	Arnell *et al*. 2005; Lehner *et al*. 2005; Aaheim *et al*. 2009; Rousseau 2013
Fishery	Temperature (e.g., Ocean temperature), ocean acidification, regional monsoon variation, severe storms	Vass *et al*. 2009; Cheung *et al*. 2013; Porter *et al*. 2014
Forestry	Temperature, precipitation, atmospheric CO_2 & O_3 conc., violent storms, frost damage, heat waves	Ciais *et al*. 2005; Karnosky *et al*. 2005; Sitch *et al*. 2007; Lavalle *et al*. 2009; Linder *et al*. 2010
Human health	Extreme weather events including heat waves, drought, heavy rain and floods, storms	Kovats *et al*. 2003; Berkhout *et al*. 2013; Piontek *et al*. 2014; Smith *et al*. 2014
Infrastructure systems, services & the built	Temperature, precipitation, sea-level rise, extreme weather events (e.g., extreme precipitation and floods, storms, heat waves, heavy snowfalls, strong	EEA 2012; Hall *et al*. 2013; 2014; Revi *et al*. 2014

environment	winds)	
Ocean systems	Temperature, salinity, CO_2, O_2, pH, light, circulation	Sen Gupta and McNeil 2012; Pörtner *et al*. 2014
River basins and floods	Temperature, precipitation, extreme events such as floods and severe droughts	Danker and Feyen 2008; Feyen *et al*. 2009; Huntjens *et al*. 2010; Ciscar *et al*. 2011; Feyen *et al*. 2012; Rojas *et al*. 2013
Tourism and recreation	Temperature, humidity, wind speed, cloud cover, snow, extreme weathers, melting of the glaciers in Antarctica	Giannakopoulos *et al*. 2005; Hamilton *et al*. 2005; Hamilton and Tol, 2007; Simpson *et al*. 2008; Aaheim *et al*. 2009
Urban areas	Changes are mainly driven by non-climate drivers but urban climate change-related risks are related to the drivers & consequences related to other sectors/ sub-systems relevant to urban areas	Satterthwaite 2008; Arnell *et al*. 2014; Revi *et al*. 2014
Water resources	Temperature, precipitation, atmospheric CO_2 conc., snow dynamics, change in the hydrology and terrestrial waster cycle	Alcamo *et al*. 2007; Arnell *et al*. 2014; Cisneros *et al*. 2014; Piontek *et al*. 2014; Schewe *et al*. 2014

Other sectors/sub-systems that can be affected by climate change also include businesses (e.g., loss of business continuity due to flooding), insurance and other financial services (e.g., implications of weather hazards on the functioning of insurance markets), and manufacturing industries (e.g., declining labour performance due to heat stress), etc. However, as highlighted in the above examples in brackets these sectors/sub-systems are mainly affected indirectly such as through the supply of raw materials, intermediates, transport, labour productivity, etc. The pressures of climate change on some sectors/sub-systems are better understood than others. Multi-sectoral and integrated climate change studies often draw on existing knowledge on individual sectors/sub-systems for integration. However, the knowledge base and associated uncertainty of the potential impacts and adaptation needs vary across the sectors/sub-systems. Hence, the availability of sufficient existing knowledge on a sector/sub-system and its responses to climate change play a crucial role in the selection of sectors/sub-systems to be incorporated in systems-thinking and integrated analysis and modelling approaches. This will have important implications for the overall uncertainty in model representation of the interactions and feedback between the sectors/sub-systems investigated. Different studies have identified some sectors/sub-systems as more affected by climate change than others, which are considered as important sectors/sub-systems in future climate adaptation and mitigation policies (e.g., EEA 2012). The selections are based on different factors such as our understanding of the system, amount of previous assessments available, confidence in the assessments, magnitude and timing of impacts, and representative coverage of a system and region under consideration (IPCC 2007). For example, agriculture is a well-studied sector/sub-system and often identified as the sector/sub-system most affected by climate change (IPCC 2007; Rosenzweig *et al*. 2014).

The following sub-sections present a more detailed review of the sectoral impacts and adaptation options and associated major sources of uncertainty for a selected number of sectors/sub-systems. The selection is based on consideration of those sectors/sub-systems that are identified as the most vulnerable and affected by climate change in Europe (Behrens *et al*. 2010), availability of sufficient knowledge on the response of the sector/sub-system to climate change (see Table 2.1), understanding of the possible interactions with other sectors/sub-systems, and associated implications for policy relevance for cross-sectoral decision-making on adaptation (Berkhout *et al*. 2013; Hibbard and Janetos 2013). These include agriculture, biodiversity, forestry, coastal and river flooding, and water resources. In addition, urban areas are included in the review as they represent concentration of much of the key and emerging climate risks such as extreme precipitation, flooding (land and coastal) and water scarcity (Revi *et al*. 2014). They also represent the key sources of non-climatic drivers of change for the other sectors/sub-systems and play an important role in the global climate adaptation as well as mitigation policies. The review includes descriptions of the sectors/sub-systems and their links with climate change and other socio-economic drivers, and the trends and projections of the potential sectoral impacts and adaptation in Europe, together with a global context.

2.1.1 Agriculture

Agricultural activities are highly dependent upon weather and climate since heat, light, and water are the main drivers of the cultivation of crops and their productivity. This highlights the complex nature of the sector/sub-system with respect to a changing climate. Climate change is already having an impact on agriculture (e.g., Peltonen-Sainio *et al*. 2010; Olesen *et al*. 2011). There is a great deal of concern about future impacts of climate change and its variability on agricultural production worldwide (Fischer *et al*. 2005; Rosenzweig and Tubiello 2006). According to the Millennium Ecosystem Assessment, the issue of global food security is identified as one of the key human activities and ecosystem services threatened by dangerous anthropogenic interference on earth’s climate (MEA 2005). Climate change is expected to continue to affect the sector/sub-system in the future, and these impacts will have local, national, regional and global dimensions (IPCC 2001). This raises concerns regarding the potential damages and benefits that may arise from future climate change impacts, as these are likely to have significant implications for future national as well as international policies, trading patterns, resources use, regional planning and welfare of citizens across different regions, including Europe. The extent and nature of these impacts will vary greatly across regions as well as over time. This will depend on different factors including, the magnitudes and timing of the changes in climate as well as socio-economic conditions, technological progress and agricultural markets, and on how the human and natural systems (including the capacity of agricultural systems) respond to these changes (Tubiello and Rosenzweig 2008).

While the overall effect of climate change on global total food production is relatively small (e.g., until 2030; Bruinsma 2003), the regional variations are projected to grow strongly with time (Parry *et al*. 2004). Some regions are affected adversely, while other regions are benefiting from an altered climate. In Europe, agricultural land is the dominant and most important land use (e.g., arable land and permanent grasslands cover more than 45% of the total area) (EEA 2005). In 2010, the utilised European agricultural area covered about 176 million ha, which consists of about 103 million ha arable land, 65 million ha grassland, and 12 million ha permanent crops (EEA 2005).

Various studies have shown that a changing climate is projected to reduce crop productivity and suitability in large parts of Southern Europe, e.g., a 25% loss in crop yields by 2080 under a 5.4^{o}C warming (Ciscar *et al*. 2011). Warmer and drier conditions in Central Europe would also lead to a moderate decline in crop yields (Trnka *et al*. 2011). On the other hand, an increase in the duration of the thermal growing season is projected to improve crop suitability and productivity in Northern Europe (Falloon and Betts 2010; Reidsma *et al*. 2010; Bindi and Olesen 2011; Olesen *et al*. 2011). Although there are some variations in the magnitude of these changes, various projections based on different climate models agree on the directions of change. In Northern Europe, the increase in crop suitability and productivity is mainly associated with the lengthened growing season and frost-free period (Olesen and Bindi 2002). On the other hand, the negative consequences of climate change on crop suitability and productivity in Southern Europe is mainly attributed to the extreme heat events and the projected overall reduction in precipitation and associated water availability in the region (Iglesias *et al*. 2010).

Other drivers such as changes in global trade, technology, demography, and policies will also cause major future changes in the spatial pattern of European agricultural land use and structure of production. For example, Busch (2006) highlighted future agricultural land use/cover changes in Western Europe is highly sensitive to global trade, and varies over time. Further, increasing flood hazards and water shortages in summer irrigation in some regions (e.g., due to earlier spring runoff peaks) could also present major challenges for future agriculture in Europe (Falloon and Betts 2010).

2.1.2 Biodiversity and ecosystems

The natural distributions of flora and fauna are determined primarily by their environmental requirements (Woodward 1987; Huntley 1999). Hence, the global biodiversity is undergoing a significant change (in terms of the number and relative abundance of species in a given biome) at unprecedented rate (Pimm *et al*. 1995; Sala *et al*. 2000) in response to a wide range of human-induced changes in the global environment (Vitousek 1994). Climate change, land use change, fragmentation, nitrogen deposition, biotic exchange, atmospheric CO_2, and disturbance are identified as some of the major drivers of global biodiversity change and loss (Sala *et al*. 2000; MEA 2005; Verboom *et al*. 2007). Climate change is already affecting biodiversity and is expected to cause a significant loss of biodiversity in the future (e.g., Pearson *et al*. 2002; Parmesan and Yohe 2003; Root *et al*. 2003; Thomas *et al*. 2004). However, different species will respond differently to a changing climate due to differences in competitive abilities, migration rates, and responses to disturbance (e.g., Malcolm and Markham 1997; Walker and Steffen 1997). Land-use change also leads to changes in biodiversity as, for example, natural areas are converted to agriculture or urban areas (e.g., Sala *et al*. 2000; Potting and Bakkes 2004; Zebisch *et al*. 2004; Reidsma *et al*. 2006). Human induced fragmentation of habitat population and ecosystems (such as due to changes in water quality and availability) also leads to loss of biodiversity as populations become too small for long-term viability (Feenstra *et al*. 1998; Verboom *et al*. 2001). Hence, reducing fragmentation and degradation of habitats (such as the construction of ecological networks, e.g., Bouwma *et al*. (2002), and the construction of local wildlife tunnels and overpasses, e.g., Forman *et al*. (2003)) are important responses to improve the ability of natural habitats to absorb and respond to future changes (Feenstra *et al*. 1998). Indirect effects from adjacent land uses (e.g., extensive farming, eco-tourism, industrial development and urbanisation) are also influential factors that lead to a decline in biodiversity (e.g., Donald *et al*. 2001). In addition, other human disturbance (such as effects due to the ever-increasing and expanding traffic flow on mammals and amphibians, Forman *et al*. (2003)) are also important factors that influence biodiversity. Globally, land use change followed by climate change has the largest effect on terrestrial ecosystems (Sala *et al*. 2000). For freshwater ecosystems biotic exchange[8] is found to be more important. In terms of regional variations, Mediterranean climate and grassland ecosystems are identified to be highly sensitivity to a large number of drivers and are projected to experience the greatest change in biodiversity. In contrast, Northern temperate ecosystems are estimated to experience the least change (Sala *et al*. 2000).

[8] Defined as 'deliberate or accidental introduction of plants and animals to an ecosystem' (Sala *et al*. 2000).

A number of studies have assessed the potential impacts of climate change on biodiversity in Europe (e.g., Huntley *et al*. 1995; Houghton *et al*. 2001; EEA 2004; Brooker and Young 2005; Schröter *et al*. 2005; Harrison *et al*. 2006). The studies have shown that impacts on the distribution of habitats vary across regions as well as types of species. The studies also highlight the important implications for EU biodiversity policy in terms of future conservation of habitats and species. For example, Harrison *et al*. (2006) estimated that there is a general pattern of a south-west to north-east shift in suitable climate space, with a balance between gains and loss for many species. Other predicted future impacts of and responses to climate change on biodiversity include continued changes in phenology (e.g., a European south to north shift of increased growing season and productivity) (Frederiksen *et al*. 2004), changes in distributions of species (Hiscock *et al*. 2004), turnover of species (Thuiller *et al*. 2005), increased disturbance by extreme events (e.g., Harrison *et al*. 2006), and disruption of communities (Berry *et al*. 2005). However, high uncertainty encompasses these estimates due to a number of factors, including uncertainty in the scenarios investigated, the spatial and temporal scales over which species respond to future changes, possible non-linearity of future responses, and the complex interactions of the direct impacts due to climate change with the indirect impacts due to other drivers such as socio-economic factors.

2.1.3 Coastal and river flooding

Flooding is among the most significant and worsening natural hazards that modern society is subjected to worldwide (Jonkman 2005; UNISDR 2011). Over the last decade, a large number of major flood events have occurred affecting several million people along with significant economic damages and costs globally (IPCC 2014; UNISDR 2009). In Europe, the two historic major coastal floods in January/February 1953 and February 1962 claimed over 2,500 lives in northwest Europe (Gerritsen 2005; Safecoast 2008; Lumbroso and Vinet 2011; Wadey *et al*. 2015). Other recent examples include the August 2002 and March/April 2006 catastrophic floods in Elbe and Danube, the severe summer floods of 2007 in the UK, and very recently, the devastating floods in Central and Eastern Europe in June 2013. According to the European Environment Agency, about 213 flood events in Europe between 1998 and 2009 alone affected more than 3 million people and caused 1126 deaths and at least €52 billion estimated loss (EEA 2010a). The total population and the economic value of assets located in flood prone areas have increased dramatically over the past decades, to which most of the increases in flood impacts are attributed (Barredo 2009; Bouwer *et al*. 2010). These trends are expected to increase further due to an overall increase in population and economic assets in flood prone areas and through more frequent heavy precipitation, increased catchment wetness and sea-level rise due to climate change (Mitchell 2003; Dankers and Feyen 2008; Feyen *et al*. 2009;

Hinkel *et al*. 2010; Rojas *et al*. 2013). Hence, flooding in Europe has caused rapidly growing concerns in recent years and has resulted in significant public, political, and scientific awareness and associated policy responses by national and transnational organisations (Mitchell 2003).

Future socio-economic impacts of river floods in Europe have been assessed by a number of studies (e.g., Feyen *et al*. 2009; Maaskant *et al*. 2009; Bouwer *et al*. 2010; Te Linde *et al*. 2011; Rojas *et al*. 2013). Unless adaptations are considered, future impacts in terms of both people affected and economic damages are projected to increase significantly (Luo *et al*. 2015). According to Rojas *et al*. (2013), the number of people affected by river floods is projected to double and annual economic flood damages could increase by almost 18-fold by 2080s with no adaptations. But when adaptations are considered, impacts reduce significantly. However, such future projections of impacts show regional variations, some areas experiencing increasing risks (e.g., Central and Northern Europe and the UK being the most affected), while other regions have decreasing or little to no change impacts (e.g., Feyen *et al*. 2009; Lugeri *et al*. 2010; Mechler *et al*. 2010; Ciscar *et al*. 2011; Bubeck *et al*. 2011; Feyen *et al*. 2012; Lung *et al*. 2012).

In terms of coastal flooding, sea-level rise and storm surges are the direct major climate-related threats to coastal habitats and human societies (Nicholls *et al*. 2007; Wong *et al*. 2013; Nicholls *et al*. 2015a). Sea-level rise can potentially lead to a range of biophysical and socio-economic impacts, threatening coastal landscapes, their ecosystem services, and coastal populations (Craft *et al*. 2009). The major direct biophysical impacts of sea-level rise include inundation of low-lying areas and loss of coastal wetlands (Hecht 2006), increased coastal flooding (Michener et al. 1997; Hecht 2006) and erosion (Cooper and Pilkey 2004), and intrusion of saltwater into estuaries, deltas and aquifers (Barth and Titus 1984; Klein and Nicholls 1999). Potential indirect impacts include altered functions of coastal ecosystems and impacts on human activities. In Europe, both the physical and economic impacts of sea-level rise are projected to increase significantly with time, especially under scenarios with higher rise in sea level, unless adaptation measures are considered (e.g., Richards and Nicholls 2009; Hinkel *et al*. 2010; Ciscar *et al*. 2011). However, there are regional variations, with the Atlantic, Northern and Southern European regions projected to be most affected in terms of people affected (Ciscar *et al*. 2011). In terms of the costs of economic flood damages, countries such as the Netherlands, Germany, France, Belgium and Denmark are identified as the most affected (Hinkel *et al*. 2010).

2.1.4 Forestry

Forests cover more than 32% of Europe's total land surface (Hanewinkel *et al*. 2013), and are as such one of the main species-rich terrestrial ecosystems (EEA 2012). They provide ranges of benefits and services such as timber, wood fibre and energy supply, recreational opportunities, as well as multiple ecosystem services (Bredemeier 2011). However, climate change and its variability have significant effect on the processes that control structure of forests and their function, and hence on their health (EEA 2012), with potentially significant loss of economic value if no effective countermeasures are in place (Hanewinkel *et al*. 2013). Historic trends and future impacts of climate change on forests include changes in growth rates, composition of plant and animal communities, phenology, increased damage due to fire and storm and insect and pathogen (IPCC 2014). Warming temperatures, changes in rainfall (amount and pattern), storms, heat waves and change in atmospheric CO_2 concentration and many other aspects of climate change are all expected to have impacts on forests (on both growth and productivity), for example, by increasing threats such as pest outbreaks, fires and drought (Olesen and Bindi 2002; Solberg *et al*. 2009; Lindner *et al*. 2010). Recent examples include the significant negative impacts of various extreme weather events such as severe windstorms and the 2003 drought in large parts of Europe (Ciais *et al*. 2005; Usbeck *et al*. 2010; Koutsias *et al*. 2012; Salis *et al*. 2013). Other potential indirect impacts include insect and fungal infestations that are generally facilitated by a warming climate.

The potential impacts show significant regional variations across Europe. Overall, climate change is projected to have a positive effect on the growing stocks in northern Europe and a negative effect in some regions in southern Europe. In Northern and Atlantic Europe, forest growth and wood production are projected to increase due to a rising temperature and increased CO_2 and nitrogen (Lindner *et al*. 2010; EEA 2012). In contrast, climate change is projected to cause adverse effects and declining productivity in Southern and Eastern Europe due to increasing drought and disturbance risks (Affolter *et al*. 2010; Bigler *et al*. 2006; Raftoyannis *et al*. 2008; Keenan *et al*. 2011; Lavalle *et al*. 2009; Silva *et al*. 2012). Moreover, future forest fires are projected to become less frequent in Northern Europe due to increase in humidity (Rosan and Hammarlund 2007). In Southern Europe, on the other hand, the risk of future wildfire is projected to increase (Dury *et al*. 2011), with an increase in the frequency of favourable conditions for high forest fire danger days (Lung *et al*. 2012) as well as the length of the fire season (Pellizzaro *et al*. 2010). Forests play an important role for climate regulation and for the global carbon cycle by storing considerable amount of terrestrial carbon. However, the overall projected increase in wildfires and associated biomass burning in Europe is likely to have important contribution to the increase in GHG emissions (Pausas *et al*. 2008). Other drivers such as windstorms (leading to increased forest damages) and forest diseases (with increased incidences observed) are also identified as important factors to future forest changes. For example, boreal forests are projected to become more vulnerable to autumn/early spring impacts of windstorms due to an expected decrease in the period of frozen soil (Gardiner *et al*. 2010). "In general, forest productivity is projected to increase in areas with increased water availability, if appropriate tree species are growing there, while it is projected to decrease where water is scarce and projected to decline further. Wherever droughts increase, forest productivity is expected to decrease" (EEA 2012, p.176). Hence, possible future responses to adapt to these impacts focus on improving resistance and resilience of ecosystems and mitigation responses to potential limits to carbon accumulation (Millar *et al*. 2007; Nabuurs *et al*. 2013).

2.1.5 Urban areas

Urbanisation is a worldwide phenomenon. Although urban areas account for less than 2% of the earth's land surface, they are home for over 50% of the world's population (Revi *et al*. 2014). This is projected to increase to 66% by 2050 (UNDESA 2014). Hence, urbanisation is an important component of studies in understanding the dynamics of future land use changes. Urban life styles and expansion of urban population and urbanised areas play an important role in the urban-rural linkages. This will, in turn, affect natural and human systems and modify land structure (Herold *et al*. 2005). This urban 'ecological footprint' as such is critical to future land use change assessments. For example, Fontaine and Rounsevell (2005) raise important questions, such as: How large will the urbanised land cover become in the future? Where will the new urban areas be located? What will be the concentration of these new areas (e.g., individual houses, flat buildings, etc.)? What are the consequences of future urban growth, such as on other land uses? What are the policy implications of new growth? What can and should be done now to avoid or mitigate negative impacts in the future? However, few urban growth predictions have been made at a city level, and even fewer at regional levels. Urban planners are aware that they need very specific information that will allow them to make strategic decisions about urban development (Cecchini 1999). Such information can be provided by decision-support and IA tools which deal with urban complexity, but which generate comprehensive results. However, without reliable information on these issues, such discussions or debates and the prospect of appropriate future planning remain at superficial level (Allen and Lu 2003).

In Europe, urban development is by far the most rapid type of land use change, with continuous urban areas projected to continue to grow at 0.5-0.7% per year (Piorr *et al*. 2011).

Although relatively small in absolute terms, this expansion rate is more than ten times higher than any other land use change. The growth in peri-urban areas (also called discontinuous – the space around urban areas which merges into the rural landscape) is even higher, i.e., four times faster than continuous urban areas. For example, the artificial land cover in Europe has increased by 3.4% (as % of year 2000) between 2000 and 2006 (EEA 2010b). In 2014, 73% of Europe's population live in urban areas, and this is projected to increase to 80% by 2050 (UNDESA 2014). While urban development generally has a range of positive effects including being an engine for economic development, rapid expansion and resulting urban sprawl has many negative social and environmental consequences. Some examples include the consumption of agricultural land, increasing problems of social segregation, urban decline, and land wastage. The potential key drivers (if poorly managed) of urban sprawl include economic (e.g., GDP change) and demographic (e.g., population change) factors, housing preferences (e.g., more space per person), social aspects (e.g., lack of green space), transportation (e.g., availability of roads) and regulatory frameworks (e.g., poor land use planning) (EEA 2006). Better understanding of these drivers is necessary to minimise the negative consequences of urbanisation and enhance the adaptive capacity of urban-rural regions (Rickebusch 2010). Hence, a better balanced and more sustainable future urban development requires increased policy attention at all scales ranging from European level to the urban-rural interface with a more holistic and territorially integrated perspective into the future (Piorr *et al*. 2011). This will have important implications on other sectors/sub-systems.

2.1.6 Water resources

Water is one of the scarce global natural resource, and freshwater remains as a fundamental element of socio-economic progress in many places, a variety of economic sectors/sub-systems competing for it (Yates 1997). The quality and availability of water resources are now critical issues due to their increasingly significant effects on human wellbeing, health of natural systems, economic growth, paths to development and markets and other human activities worldwide. A number of studies have demonstrated the important implications of global water security issues (e.g., Hanjira and Qureshi 2010; Hejazi *et al*. 2014). Important drivers affecting the sustainability of freshwater systems through increased demand or decreased supply of water include: (a) climatic factors such as increasing temperature and associated potential evaporation and precipitation), and (b) non-climatic drivers such as economic development, population increase, urbanisation, technological changes, lifestyle changes, and land use or natural geomorphic changes (Dalin *et al*. 2012; Cisneros *et al*. 2014). In Europe, energy production (primarily for cooling) accounts for 44% of the total water abstraction, while agriculture represents 24%, public water supply (domestic use) for 21%, and 11% for industrial purposes (EEA 2009). However, there are regional variations across Europe. For example, in Western Europe more than 50% of water abstracted is used for energy production (as cooling water), even reaching up to two-thirds in Belgium and Germany (EEA 2005). On the other hand, in Southern Europe more than 50% is used for agriculture.

Water availability from surface water and groundwater resources in Europe is estimated to decline significantly due to climate change. This is related to the increased demand for water from other sectors/sub-systems such as domestic use, agriculture, and energy and industry, as well as cross-sectoral implications, which are still poorly understood (IPCC 2014). Future projections show growing differences in water resources between Southern and Northern Europe (Alcamo *et al*. 2007). There is a significant decline in total runoff and groundwater resources projected for the Mediterranean region (Olesen *et al*. 2011). Future climate change is also projected to negatively affect water quality in several ways, with important implications for other sectors/sub-systems, such as agriculture and forestry, human and animal health and aquatic ecosystems functioning (IPCC 2014). For example, increasing precipitation in winter and less rainfall in summer could increase nitrate leakage (Kersebaum *et al*. 2008) that could potentially have negative implications on water quality (Bindi and Olesen 2011). Decreases in precipitation may also lead to low flows, thereby increasing concentrations of chemical and biological contaminants that will affect the quality of freshwater resources (Boxall *et al*. 2009).

The water exploitation index (WEI, also termed as 'withdrawals-to-availability' index and defined as the ratio of mean annual total abstraction to the mean annual total freshwater renewable resource) is the commonly used indicator of the pressure/stress on freshwater resources. The extent of water stress is defined based on threshold values categorised as no-stress ($WEI \leq 0.1$), and low ($0.1 < WEI \leq 0.2$), medium ($0.2 < WEI \leq 0.4$), and sever ($WEI > 0.4$) stress (Raskin *et al.* 1997). The indicator has an advantage in reflecting the combined effects of the pressures both from human society (which reflects the demand side) and the hydrological system (which reflects the supply side). Based on the above thresholds, eight European countries are identified as water stressed (with $WEI > 0.2$). These include Germany, England and Wales, Italy, Malta, Belgium, Spain, Bulgaria, and Cyprus (Cyprus with $WEI > 0.4$) (EEA 2005). According to Henrichs *et al*. (2002), a marked overall increasing trend in water stress is estimated for Europe due to increasing water use in Eastern Europe accompanied by decreasing water availability in most of Southern Europe. Understanding the potential future impacts of climate change on Europe's freshwater resources as well as the effects of future socio-economic development and associated increase in water demands (in terms of both quantity and quality) is of a great concern for people's lives and the economy (EEA 2007). Hence, appropriate future management of freshwater resources requires a better understanding of the complex interactions of the natural processes, technology, economics, institutions, and other socio-economic activities in order to balance water supply with water demand.

2.2 Climate & Socio-Economic Change Impacts & Adaptation: Assessment Methods & Tools

Assessments of the effects of climate change can be based on three methodological approaches (see Kates 1985; Parry and Carter 1988; Parry 1990; Parry and Martens 1999). First: *Impact (also termed as 'If-Then-What') approach*: this follows a straightforward 'cause and effect' pathway to estimate the impact that a climatic factor has on an exposure unit (e.g., activity). It assumes that non-climatic drivers are unchanged. Applications of such assessment approach have drawbacks including: a focus on climate drivers only (ignoring the effect of other factors), reliance on the choice of the climate driver (which may not always reflect the climate-sensitivity of the unit being investigated), and failure to assign likelihood to the assumed changes in climatic factors (providing limited information for response action). Second: *Interaction (also termed as 'What-Then-If') approach*: this recognises the additional effects of external factors and associated feedbacks, and focuses on "What points of a system are sensitive to what types of climatic change and then what might the impact be if those changes in climate were to occur?" (Martens and Rotmans 1999; p.203). Third: *Integrated* approach: this is a comprehensive consideration of the various interactions between climatic as well as non-climatic factors driven by changes associated with society.

Impact assessment approaches have evolved rapidly since the 1980s when climate change became a policy concern globally. A particular focus has been on development of assessment methods and tools mainly looking at biophysical impacts (e.g., loss of land due to flooding and erosion) for economic values (such as agriculture or forestry) or other essential values (such as biodiversity) (e.g., McMichael *et al*. 2003). Despite the global and cross-boundary nature of climate change impacts and the rapid development of different methods, there was a lack of a structured framework and guidance on model and tool developments. The Intergovernmental Panel on Climate Change (IPCC) produced a standardised methodological framework and guidelines for ensuring standardization of methods and application across different sectors/sub-systems, disciplines, and scales (Carter *et al*. 1994). This framework defines seven generic steps: (1) Problem definitions, (2) Selection of the methods, (3) Testing of the methods (e.g., sensitivity analysis), (4) Selection and application of the climate change scenarios, (5) Assessment of the biophysical and socio-economic impacts, (6) Assessment of autonomous adjustments, and (7) Evaluation of adaptation strategies. The framework uses a top-down approach, where scenarios of climate change are used as input to large-scale biophysical models for a systematic quantification of the severity of the impacts of climate change (Parry and Carter 1998).

Many climate change impact assessments still follow this broad IPCC framework. However, most assessments have limited applications for assessing impacts due to non-climatic drivers such as changes in socio-economic and human systems. This is due to the focus on climate change-driven impacts, rather than on current vulnerabilities or adaptive measures (Burton *et al*. 2002). The results of such assessments can be sensitive to the uncertainties in the climate models (Dessai and Hulme 2007). In addition, since adaptation responses often show a high degree of variability between countries, they are difficult to describe using generic approaches (Klein *et al*. 1999; Smit *et al*. 2000). Further developments of models recognise (at least parts of) these limitations, focussing on increasingly improved assessment models for the purpose of adaptation assessments (Burton *et al*. 2002; Dessai *et al*. 2005). This has led to the development of a wide range of impacts and adaptation assessment approaches or methods and tools with varying advantages and limitations.

According to Parker *et al*. (2002), models are broadly classified into: (i) data models that are representation of measurements and experiments, (ii) qualitative, conceptual (or mental) models as verbal or visual descriptions of systems and processes involved, (iii) quantitative numerical methods that are formalisation of qualitative models, (iv) mathematical methods and models that are used to analyse the numerical models and interpret the results, and (v) decision-making models that transform the values and knowledge into actions. There are different types of modelling approaches and models that can provide the capacity to integrate different types and forms of knowledge from various sources for assessing complex systems problems (e.g., Letcher *et al*. 2013). IA modelling processes involve integrating these various models in a transparent and interactive framework that allows for participation of stakeholders at all stages of the process (Parker *et al*. 2002). Following Letcher *et al*. (2013), short descriptions of five most commonly used types of system modelling approaches are presented below.

2.2.1 Knowledge-based modelling approach

These types of models (also called conceptual models) are based on qualitative and quantitative data and information, where knowledge about a system (e.g., forest species suitability distribution in the Ecological Site Classification (ESC) decision-support tool; Ray 2008) is gathered from experts (or incorporated in *expert systems*) and formalised in a knowledge base so that conclusions can be drawn via an inference engine using logic (Davis 1995; Chen *et* *al*. 2008). Such models can be classified into two groups: (a) *rule-based* those formalised by a set of 'if-then-else' rules and (b) *frame-based* those expressed as a series of facts formalised based on a pre-defined logic system (Sajja and Akerkar 2010). These models are generally 'trained' based on the user's experience and the inputs of knowledge used to define the system. The commonly used training process is called 'knowledge elicitation' (Shadbolt and Smart 2014). This process is based on expert knowledge, in contrast to other types of models such as Artificial Neural Networks (ANNs), where the knowledge is often learnt directly from data. The main difference is that the knowledge elicited from the expert is explicitly encoded in facts and rules and it can be also used to explain deductions based on chains of rule applications, something which is not trivially available in data-driven models.

These types of models are useful for providing an initial understanding of how a given system works and are often used for fairly simple management and decision-making. They combine as much high-level expertise obtained from experts in the field as possible (e.g., Herrore-Jiménez 2012). However, such approaches involve a high level of uncertainty. Uncertainty in these models can be incorporated, which is often based on expert judgment for simple models. One of the common approaches for accounting uncertainty in such models is Fuzzy Set Theory (e.g., Klir and Yuan 1995; Dokas *et al*. 2009; Chevalier *et al*. 2012), which is used in a range of applications including decision theory, expert systems, and management science (Zimmermann 2010). Other applications of fuzzy set approaches include stakeholder-led scenario development (e.g., Gramberger *et al*. 2011). Despite the advantage in terms of using established comprehensive knowledge of processes to understand a system, they have limited applications for problems that are too complex to be formalised using knowledge-based models, or when the knowledge of the relevant processes within a system is incomplete or uncertain (Letcher *et al*. 2013).

2.2.2 Agent-based modelling approach

These types of modelling (also known as *individual-based modelling*) approaches focus on an explicit representation of discrete/autonomous agents (individual or collective entities) in a system and their interactions with each other and their environment. Some examples of such agents modelled include people (e.g., Gilbert 2008; Filatova *et al*. 2011; Le *et al*. 2012; Crooks and Wise 2013), animals (Drogoul and Ferber 1994), cities (Crooks 2006; Hosseinalli *et al*. 2013), groups (e.g., Sanders *et al*. 1997), or biophysical entities such as water (e.g., Servat *et al*. 1998). Such models are associated with an 'object-oriented' associated style of modelling, based on the multi-agent system model that features autonomous entities in a common environment able to act on it and communicate with an internal objective (Ferber 1999).

Agent-based modelling (ABM) has both experimental and mathematical styles of thinking and such models are based on a representation of two or more agents that exist in an environment and at given time with shared resources which eventually communicate with each other and their environment. Agents are representation of real-world individuals/biophysical entities that are typically able to react to perceived changes in their environment through action on the environment or internal adaptation (Letcher *et al*. 2013). Such environments are characterised by space (which could be either discrete or continuous), or by networks (defined, for example, with a GIS map) in which agents behave and interact. Hence, a rule-based representation of the behaviour of agents (e.g., how they move around) and/or how they interact with each other and with their environment is a typical characteristic of agent-based models.

Agent-based modelling approaches provide more appropriate theoretical, quantitative and mechanistic methods (e.g. for understanding, explanation and prediction of a phenomena) than for example knowledge-based models. A fundamental focus and advantage of agent-based modelling approaches is the discovery and explanation of emergent behaviours or characteristics of complex systems, for example, patterns of behaviour and organisations generated by a system's component interactions. Such approaches provide large-scale outcomes based on understanding the simple interactions and learning among the individual components (Letcher *et al*. 2013). "Agent-based models are also developed and applied to incorporate complex cognitive representations of individuals' mental models, behaviours and choices, such as with the Belief-desire-intention (BDI) model (Rao and Georgeff 19951987). Hence, agent-based models can also explore, for example, how the attitudes of individuals or the institutional setting can affect system-level outcomes (Pahl-Wostl 2005). For this reason they are particularly useful for social learning applications. The conceptual framework for an agent-based model usually describes the interaction of autonomous entities, as well as their links and their behavioural patterns" (Letcher *et al*. 2013, p.173).

2.2.3 Multicomponent models coupling approach

These types of modelling approaches involve integration/coupling of stand-alone and/or semi-independent individual component models from different disciplines or sectors/sub-systems into a comprehensive and integrated package (e.g., Larson *et al*. 2005; He and Ding 2005; van Delden *et al*. 2011; Drobinski *et al*. 2012; Edwards *et al*. 2013; Laniak *et al*. 2013; Kraucunas *et al*. 2015). For example, the coupled computer model, the Community Climate System Model (CCSM), consists of four semi-independent component models for the atmosphere, ocean, sea-ice, and land-surface. These component models interact through a flux-coupler component within a distributed multi-processor environment, and are used for simulating the long-term global climate (Drake *et al*. 2005). There is a growing trend in developing large and complex applications of such modelling approaches associated with the rapid increase in computing power of distributed-memory computers and clusters of symmetric multi-processors applications.

The coupling process can include the integration of different component models that are developed using different modelling approaches (e.g., knowledge- or agent-based). The linking of such approaches is often used in different multi-disciplinary studies, which involve integrating social, economic and biophysical components of a system being investigated. "In such cases, the biophysical models often use the process-based computationally intensive models that take into account the spatial and temporal distribution, while the social and economic models often use the knowledge-based or agent-based models (e.g., van Delden *et al*. 2007)" (Letcher *et al*. 2013, p.172). Generally, the conceptual framework for integrating component models represents links between components of the system, so that nodes often represent detailed component models, while links represent the transfer of data between the component models. Such coupled models can sometimes consider incorporating feedbacks between component models (Letcher *et al*. 2013).

Depending on the purpose of the modelling application, the linking of the component models could be: (1) *loose*, (also called 'soft-linking' of models) where data transfer between the component models can be done manually or outside the modelling process (e.g., outputs from one model are used as input to another model, or another example is soft-linking of expert judgments in an expert panel) (e.g., Deane *et al*. 2012), or (2) *tight* ('hard linking' of models) where the component models are internally linked together and share inputs and outputs dynamically (e.g., Rivington *et al*. 2007), or (3) a combination of the two (e.g., de Juan *et al*. 2000). The component models can be recognised as stand-alone or semi-independent models or no longer identified as separate entities as they are specifically designed as part of a single computer code to work together within the coupled system to the extent that they cannot be run without the whole computer code or without requiring extensive recoding (Feenstra *et al*. 1998; Letcher *et al*. 2013). Qualitative integrated assessments can provide useful insights, particularly when quantitative integrated analysis is not possible. The well-known example of such approaches is one used in the IPCC's 'Burning Embers diagram' in its Third Assessment Report (TAR) based on expert elicitation in identifying the risks of climate change into five global 'reasons for concern' (Smith *et al*. 2001; 2009). One of the issues in qualitative integrated approaches (e.g., soft-linking) in impacts and adaptation assessment is the potential risk of 'overlap' and hence potential double counting of impacts. In addition, such approaches could be affected by lack of consistent scenarios across different sectors/sub-systems, which make any useful comparison across sectors/sub-systems or aggregation of impacts across regions very difficult. These factors are taken into account in quantitative integrated impact analysis (from soft-linking to hard-linking to integrated modelling) through linking of sectoral models by which outputs of one model/study are used as inputs to another model/study dynamically.

Another emerging example of coupling of component models in systems modelling includes *meta-modelling* approaches. Here, simple concepts are derived from complex models, and these concepts are integrated into a new model, i.e., they are models of models. Such approaches can use regression (e.g., Piñeros Garcet *et al*. 2006) or model reduction methods (e.g., Ratto *et al*. 2012), among others. Meta-models are an abstract description of a more complex model, by neglecting the less important aspects of a system while concentrating on the key parts of or processes within the system being investigated (Gholizadeh and Azgomi 2010). Such approaches help us to understand more complex phenomena and systems in a consistent and unified manner, which otherwise are difficult to understand or are computationally intensive to model using complex detailed models.

Some of the key advantages of combining different component models in a single integrated modelling system include: easy, efficient and transparent transfer of data between component models; reduced simulation time due to availability of data transfer efficiency and installation of models on powerful servers; improved control over the processes and data flow and facilitating the design of multi-disciplinary projects due to centralisation of the tools and data; and the standardisation of robust methods and tools allowing users to carryout inter-comparison of studies in different areas. A typical example of model coupling for an integrated analysis is the Community Integrated Assessment System (CIAS, Warren *et al*. 2008). CIAS brings together a wide range of disparate numerical models and climate-related datasets from the academic research community into a common framework. The CIAS aims to address some of the key challenges in the field, as posed by Risbey *et al*. (1996), which include: (1) connecting alternative sets of component modules together and providing a flexible and multi-modular platform, which facilitates iterative interaction with stakeholders and allows for addressing a range of policy questions, (2) operating a distributed model system deployed across wide ranges of institutions in different countries, which promotes greater diversity and comprehensiveness of modelling components, drawing on a wide range of international expertise, and (3) enabling models to communicate with each other regardless of operating system or computer language (PROVIA 2013a).

2.2.4 Bayesian network approach

Bayesian networks (also sometimes referred as '*belief networks*', '*knowledge maps*', '*probabilistic causal networks*', etc.) are method of reasoning using probabilities by combining graph theory, probability theory, computer science and statistics (Ben-Gal 2007; Knipping 2012). The notion of Bayesian networks is first introduced in 1985 (Pearl 1985; 1988) to emphasize three key aspects: (i) the subjective nature of the input data information; (ii) the reliance on Bayes's conditioning as the basis for information updating; and (iii) the distinction between causal and evidential modes of reasoning (Knipping 2012). These graphical modelling approaches are most commonly used for decision-making and management applications where uncertainty is a key consideration (e.g., Ames 2002; Varis 2002; Bromley *et al*. 2005; Newton 2010; Daly *et al*. 2011; Düspohl *et al*. 2012).

Bayesian networks belong to the family of graphical models and use probabilistic rather than deterministic relationships to describe the connections between different system variables within the graphical structures (Borsuk *et al*. 2004). In particular, the nodes in the Bayesian networks represent random variables that are connected by arrows (also called 'edges') which represent the probabilistic causal dependences (characterized by a conditional probability distribution for the variable at the head of an arrow, given all possible values of its 'parents' at the tails of arrows) or an aggregate summary of complex associations (Reckhow 2003). Variables without parents are represented by unconditional (i.e., marginal) distributions. The conditional dependencies between the variables in the graph are often estimated by using known statistical and computational methods (Borsuk *et al*. 2004; Ben-Gal 2007).

The two main advantages of Bayesian networks are: (a) their compact and efficient representation of large probability distributions, and (b) the use of inference algorithms that can answer queries about these probability distributions without the necessity for constructing them explicitly (Darwiche 2008). The construction of Bayesian networks can be done based on either an expert knowledge base or by learning them from data, or a combination of the two. There are certain specialized types of Bayesian networks that deal with systems that demand for being slightly more structured than the general Bayesian network (Daly *et al*. 2011). The three main types are (1) causal interaction (or interdependence) models, which assume that the parents of nodes in the graphical structure are, to some degree, independent of each other (e.g., Meek and Heckerman 1997), (2) dynamic Bayesian networks, which allows to model temporal processes based on a two-part specification of the initial conditions of the variables (using *a prior BN*) and how they change with time (using *a transitions BN*) (Although feedback loops cannot be conveniently represented in Bayesian networks, time steps can be used in such approaches to describe such effects; e.g., Borsuk *et al*. 2006), and (3) influence diagrams, also known as Bayesian decision networks are Bayesian networks that include decision (i.e., management) and utility (i.e., monetary and non-monetary cost-benefit) variables (e.g., Ames 2002).

2.2.5 System dynamics modelling approach

System dynamics modelling approaches are characterised by a perspective and set of conceptual tools and numerical methods that are used for understanding and modelling of the structure and behavioural dynamics of complex systems[9], such as expressing the temporal cause-and-effect relationships between different interacting variables (Gilbert 2008). They are rigorous modelling techniques used to build formal computer simulations of complex systems in order to provide a holistic and dynamic (rather than static) view of the system and be able to design more effective policies and organisations (Sterman 2000). The earliest and well known examples of system dynamics modelling approaches are large scale computer models of the world by Forrester (1971, *The World Dynamics*) and Meadows *et al*. (1972, *The Limits to Growth*). For example, Forrester (1971), the founder of system dynamics, developed and applied a global model to predict future levels of population, growing pollution, and rates of consumption of natural resources. According to Forrester (1971), the method in systems dynamics includes three main principles: (1) feedback control theory, (2) understanding the decision-making process, and (3) the use of computer-based technologies to develop simulation models. The system dynamics modelling approaches often deal with aggregated views concentrating on long-term policy strategies, rather than dealing with individual agents like other models such as the agent-based modelling approach. How to view system dynamics, for example, as a philosophy, or paradigm, or methodology, as well as its epistemological and ontological stance (positivist or interpretivist) has been a debate (Lane 2001). The philosophy of system dynamics in essence is system formalism based on ordinary differential (or rather difference) equations, which is formulated when the dynamic hypothesis is converted into a 'stocks and flows' representation, where *stocks* (also called accumulators/levels) represent the system state variables (Sterman 2000), while *flows* (also known as rates) are the processes that influence change in the stock levels (Letcher *et al*. 2013). A simulation engine is used to run the numerical model, and simulate the change in the values of stocks and flows over time.

These modelling techniques model systems of different interacting variables which allow handling: (1) direct causal links between the interacting variables, e.g., population growth is linked to increased depletion of resources, and (2) feedback loops, e.g., population growth

[9] A complex system can be considered as a system made up of multiple components which interact with each other in complex ways. Understanding of such a system requires identifying and evaluating the key potential interactions between the components.

depends on the food supply, but food supply depends on the level of the population (Sterman 2000). In many system dynamics applications, there is often an emphasis on two important aspects of the modelling process: (1) eliciting the causal assumptions that end users have about the system (referred as mental models), and developing models that test the accuracy and reliability of these assumptions, and (2) engaging end users and stakeholders in a modelling process which fosters the values of openness, diversity, and self-reflection (i.e., social learning purpose) (Costanza and Ruth 1998). Based on these ideas, a number of system dynamics-based modelling approaches have emerged, such as: mediated modelling (van den Belt 2004; Metcalf *et al*. 2010) and group model building (Vennix 1996).

Each of the five types of modelling approaches described above (Sections 2.2.1-2.2.5) has their respective benefits and limitations. Letcher *et al*. (2013) have highlighted that the selection and applications of appropriate assessment models often depend on five key factors, which include: (1) the main purpose or type of the model (e.g., prediction, forecasting, management and decision-making under uncertainty, social learning, and developing system understanding or experimentation), (2) type and availability of data (e.g., qualitative or quantitative), (3) type of end users and associated output requirements regarding the scales (spatial and/or temporal) and structure of the expected model outputs (e.g., estimating the average/aggregated/distributional characteristics of a population/phenomenon or modelling individual elements of a system and associated interactions with each other and their environment), (4) treatment of uncertainty (e.g., uncertainties in data and measurements used for model parameterisation, or in the inputs used, or in lack of system understanding such as which processes to consider and how different processes interact), and (5) approaches used for resolving the model (e.g., scenario/'what-if'-based analysis, analytical equations often used for simpler models, and optimization approaches, where the choice of an approach is dependent on computational, theoretical, and end user considerations). The following section describes different types of integrated assessments and modelling approaches. This has a focus on the main types and mechanisms of integration in an application of the different methods described above for an integrated assessment of potential impacts and management of environmental issues (Kelly *et al*. 2013). This is an important factor in evaluating the strengths and limitations of existing IAMs (Section 2.4).

2.3 Climate Change Integrated Assessments: Systems Integration Approaches

One of the major challenges of climate change is that impacts are often characterised by multiple interconnected systems involving complex interactions, feedbacks, and trade-offs between human activities and environmental processes that cross boundaries of sectors/sub-systems, spatio-temporal scales as well as levels of governance and management responses (Jakeman and Letcher 2003; Hibbard and Janetos 2013; PROVIA 2013b). For example, the rising demands of a rapidly growing population for food, water, materials, energy, and other resources will put increasing pressures on land use, water resources and ecosystems. Increased energy use leads to increased demands for cooling water for thermal power plants. Howells *et al*. (2013) argued that the lack of holistic integration in resource assessments and policy-making processes often results in inconsistent strategies and poor management of use of resources. Jakeman and Letcher (2003) also highlighted the need to meet the challenges of sustainability and catchment management in terms of assessing resource usage options and environmental impacts integratively. The planning and implementation of appropriate policies require a holistic understanding of the relevant system processes (such as biophysical, social, economic and political), their complex interactions, and their response to future changes (Letcher *et al*. 2013). These highlight the need for integrated modelling approaches for assessing future impacts and the potential trade-offs and synergies between different alternative management policies across sectors/sub-systems and regions.

However, most climate change impact assessments often focus on a certain system in a certain place in isolation from other systems and places (Feenstra *et al*. 1998). Although isolated and sector-specific studies may generate important information on the potential impacts of climate change with greater details, these analysis may lead to inconsistencies and potential over- or under-estimation of impacts. This could results in failure to address in capturing the complex interactions of climate change impacts phenomena, for example, involving competition of different sectors/sub-systems for land and water resources, as well as interaction through economy, society, and politics. For example, the extent and productivity of agricultural land depends on a combination of different factors such as, land availability, water supply, weather conditions, technological improvements, market demand, etc., of which the interactions are rather complicated (Hibbard and Janetos 2013; Howells *et al*. 2013). Hence, an assessment of climate change impacts focusing on the agriculture sector/sub-system alone, by maintaining other sectoral water usages unchanged could potentially overestimate the irrigation water use, and hence adaptation needed. Another example is that crop yields in one place can be affected by changes in market prices that are determined by yields of competing crops or yields produced elsewhere. Given the complexities of such interactions, developing a comprehensive understanding of interdependent systems is challenging. It will be even more difficult for assessing how multiple interacting sectors/sub-systems may be affected by changing future climate and socio-economic conditions and how holistic adaptation strategies can be developed and implemented across different scales (PROVIA 2013b). This highlights the need for a unified, science-based approach. Applications of such integrated holistic approaches in impact assessments take into account key interactions and feedbacks and tradeoffs within and between sectors/sub-systems of a particular system, and across different systems (Hall *et al*. 2013). Integrated modelling is a systems analysis-based approach, which incorporate a range of interdependent components (e.g., methods, models, processes, stakeholders, etc.) that together form the basis for constructing an appropriate modelling system.

The three major reasons why integration in climate change studies is important are: (1) impacts do not happen in isolation (i.e., impacts in one sector/sub-system can affect another sector/sub-system positively or adversely; some sectors/sub-systems are affected by climate change directly and/or indirectly; and sectoral linkages and interactions could reduce or amplify impacts between sectors/sub-systems), (2) the issues addressed in climate change impacts and adaptation are dynamic in nature, and (3) integration is often necessary for prioritizing vulnerable regions and sectors/sub-systems and their associated adaptation needs. For example, Cohen *et al*. (1998), identified three important aims of integrated climate change studies: (i) to generate a holistic assessment of the overall impacts across multiple sectors/sub-systems, which can be greater than the sum of the individual sectoral impacts, (ii) to provide a better understanding of the potential impacts of climate change in a broader context (e.g., economic development, sustainability of ecosystems or resource management) and answer the wider questions in terms of the directions and magnitudes of change in relation to the benefits of different management interventions, and (iii) to generate comprehensive science-based and policy-relevant information for stakeholders and decision-makers in order to assist them designing robust adaptation policy options. To achieve this, holistic climate change impacts and adaptation assessment approaches need to consider integrating over different dimensions as well as to different degrees of integration (Jakeman and Letcher 2003; Letcher *et al*. 2013). These include the consideration of the key disciplines within and between the human and natural systems, multiple issues and stakeholders, multiple scales of system behaviour, models of the different system components, the spatial and temporal cascading effects, and multiple databases. There are five main types of integration considered in different integrated assessment and modelling approaches (Letcher *et al*. 2013). The following sub-sections present short descriptions of these.

2.3.1 Multiple sectors/sub-systems or issues

This approach involves an integrated consideration of two or more sectors/sub-systems or issues in a system. Such integration is required as measures for different natural resource management problems have indirect consequences on other socio-economic and environmental issues. Hence, taking into account the combined effects of management responses provide improved management decisions to reduce the potential negative indirect effects. This type of integration is part of a system-wide (also called 'whole' system) approach by covering the whole, or at least the main parts of a system. Such an approach draws heavily on lessons learnt from sector-wide approaches used successfully in areas such as agriculture and water sectors/sub-systems. The system under consideration can be sub-divided into component sub-systems based on more focused issues. There is a difference between 'integrated' and 'integral' modelling in terms of the ways to perform the integration process as particularly defined by Voinov and Shugrat (2013). In the case of 'integrated' modelling, the 'whole' system is treated as a group of autonomous components, which represent different sectors/sub-systems (e.g., agriculture, water, etc.). In the case of 'integral' modelling, on the other hand, integration is performed by concurrent treatment of all the sub-systems as an integral part of the 'whole' system. This can be considered as a first step in the process of integration, and it may include other forms of integration, such as stakeholder involvement (Letcher *et al*. 2013).

2.3.2 Multiple processes and models

This approach involves integration of two or more processes (representing physical, economic, social, or environmental issues) within a system (e.g., van Ittersum *et al*. 2008; Henrichs *et al*. 2002) or combining models of different systems (e.g., Hall *et al*. 2013; Laniak *et al*. 2013). This approach can involve modelling of each process separately and integrating each model to form a specific systems integrated model. Such integration may also require combining disparate modelling methods from different disciplines. The integration can be achieved in many ways, such as soft-linking or hard-linking of the component models or complete integrated representation of the systems as one single model. In the latter case, the component models can no longer be used independently without significant improvement (Section 2.2.3).

2.3.3 Multiple disciplines

Integrated approaches by nature are interdisciplinary undertakings, which are based on concepts and methods of its component disciplines (e.g., Tress *et al*. 2005). Hence, such approach involves integration of two or more disciplinary views of environmental or management issues/problems and their accompanying boundaries of the system representing the issues under investigation. The formalisation process requires an integrated understanding of the system drawing on knowledge from research in multiple disciplines and cooperation with relevant interest groups. However, transforming this integrated but complex knowledge into a formalised model is often challenging. One example of such integration is Bayesian networks (BNs) that graphically and probabilistically represent relationships among variables from different disciplines (e.g., Barton *et al*. 2012). Such tools are often used to integrating multiple lines of evidence, including process-related information from existing data and expert judgment across different disciplines to assist, for example, ecological risk-based decision making.

2.3.4 Across different scales of assessment

Environmental problems can be considered at various scales, since different parts of a system representing such issues may operate at different spatial-temporal scales. Understanding the relationships between (different macro-/micro-scale) processes/phenomena, their short- and long-term changes, and their associated relations across scales within a system is one of the major challenges of science (Kates *et al*. 2002; Wilbanks 2002; Ewert *et al*. 2009). Organisational scale[10] can also be important for understanding systems that function on several spatio-temporal scales (e.g., Weston and Ruth 1997). For example, when assessing hydrology-related issues (in terms of the climate drivers) catchment boundaries may represent an appropriate scale, but scales of the social, political, economic, and technological factors are likely to vary. Furthermore, the various inter-linked sub-systems within a certain component of a target system may also operate at different scales. For example, the groundwater and surface water as parts of a hydrological system within a certain region also operate often at different scales (both in time and space). Hence, integration of a system across such different scales requires a comprehensive understanding of how a system and associated components change with time and space. Multi-scale nesting approaches are often used in treatment of issues at different scales. However, computational (e.g., power and model run times) constraints as well as lack of sufficient knowledge on how a system (and its components) responds at different scales is a challenge. This highlights the need for a compromise between the scales of representing component issues/processes for understanding the major components of cross-scale dynamics in global change processes (Wilbanks 2002). For example, van Delden *et al*. (2011) identified four major factors in selecting appropriate scale for integrated modelling approach in support of policy. These include: (i) the scale at which the process/phenomena occur or can be represented in the model, (ii)_end user or stakeholders' scale requirement, (iii) the linkages and integration between components of the model that represent different processes across different scales, and (iv) practical constraints including data availability or computational limitations.

[10] An example is a hierarchical system in agriculture such as the organisation of agricultural systems (e.g., for food production) with levels such as field, farm, region, country, continent and globe (e.g., FAO 1997).

2.3.5 *Integrating knowledge from and across multiple stakeholders*

Information on climate change impacts is used by a range of stakeholders including: policy makers, the national and international development community, national treasuries and multi-lateral funding agencies and the public, although their needs and interests may differ (Vivid Economics 2011). Integration with and among stakeholders (also referred as participatory modelling) has been a growing area of interests that has spanned both the environmental modelling as well as the environmental social science community (Voinov and Bousquet 2010). Main reasons for this acceptance is attributed to: (1) model-based reasoning has become a predominant and preferred basis of environmental decision-making in environmental issues, (2) public participation has become an essential component to informed decision-making, and (3) stakeholder groups often hold unique and complex knowledge that is useful for understanding the dynamics of social-ecological systems. Hence, integrating stakeholder views and knowledge at all stages of the systems model building process allows decision-makers: (i) to understand important conceptual components in the environmental systems being managed, (ii) to build trust and common understanding between potentially diverse sets of competing groups, (iii) to promote learning among decision-makers, and (iv) to reduce uncertainty by extracting important information and new insights that might not otherwise be a part of scientific assessment performed by experts alone.

However, some questions about the degree of participation that certain processes and tools afford still remain: Who is learning from whom during the modelling processes? What are the ultimate goals of individual, public or modelling endeavours? Who benefits from such knowledge? The level and success of integration at which IAM outputs are utilized by stakeholders depends on the degree and nature of stakeholders' participation and relevance of model outputs (Krueger *et al*. 2012). Such integration can be done at the various stages of the modelling process, for example, in prioritizing the research questions, providing data that populates a model, developing future scenarios, or constructing a conceptual model that will serve as the basis for future empirical modelling. These factors depend on the knowledge being used and for what purpose/benefit of generating the model or in the process of modelling or learning and for what reason.

It is worth noting, however, that the integration approaches described above (Sections 2.3.1-2.3.5) are not mutually exclusive (e.g., Kelly *et al*. 2013). For example, integration of processes or disciplines or coupling of models may also involve the integration of different sectors/sub-systems, issues and scales. In addition, integrated treatment of different issues such as physical, social, economic or environmental may necessitate an integrated modelling approach across various scales. Furthermore, with the growing interest in participatory modelling in climate change studies, integration with and among stakeholders is becoming a common feature of IA exercises. However, some important challenges in achieving the objectives of IA modelling approaches (that are not possible by sector-specific studies) include: (i) the additional needs that are placed on component studies/models within the IAMs, (ii) lack of sufficient knowledge of the complex interactions and feedbacks between the sectors/sub-systems, and (iii) its multi- as well as inter-disciplinary nature and associated challenges.

The practical application of IA methods and models for climate change adaptation policy-making remains as a key research agenda in the scientific community. This is demonstrated by the recent rapidly growing number of multi- and inter-disciplinary integrated research projects (e.g., CLIMSAVE, DINAS-COAST, ERMITAGE, IMPRESSIONS, MEDIATION, PESETA, RESPONSES, RISES-AM). These studies involve a significant cooperation among the scientific community from different disciplines as well as with different concerned stakeholders and decision-makers. As a result, there is a range of complex systems integrated modelling frameworks. The following section presents a review of existing IAMs which uses different modelling approaches and integration methods discussed in Sections 2.2 and 2.3. The review focusses on regional (or continental) scale assessments. This is due to the need for understanding regional phenomenon and earth system processes (including both human activities and environmental systems) that influences adaptation policy and decision-making which require integrated approaches that takes into account these regional changes (see Hibbard and Janetos 2013).

2.4 Review and Appraisal of Existing Integrated Assessment Models and Frameworks

2.4.1 Integrated assessment models: uses and limitations

Most IAMs combine dynamic descriptions of the climate and energy-economy system, and climate impacts to support the design of climate change policies (Mastrandrea 2010; Füssel 2010). They are now increasingly considered as holistic approaches to address the complex issues of sustainability and sustainable development under a changing climate (Harris 2002; Krajnc and Glavič 2005) and to support and inform risk management and adaptation policy decision-making (Rotmans *et al*. 1990; Rotmans and van Asselt 1996; Liu *et al*. 2015). There is a growing awareness among policymakers to support policy development using IA modelling. For example, the European Commission (EC) has recently introduced impact assessment of its climate change policies as an essential step in the development and introduction of new policies (EC 2005), for which IAMs play an important supporting role in assisting the decision-making process. However, despite the advancement in computational power some of these complex IAMs still tend to be very demanding of data, expertise, as well as time for model building, testing and application, which often limit their effective use (PROVIA 2013a). Hence, the main benefit of a model-based integrated analysis often tends to focus on assessing the broader effects of climate change by integrating biophysical and socio-economic models (PROVIA 2013a).

There are wide ranges of IAMs that are developed for different goals and objectives and at different scales in order to assess the issues of climate change. This mainly reflects the diversity in the context of examining the potential impacts of and the decision-making related to global climate change issues and response policies as well as the variety of underlying scientific disciplines involved (e.g., Füssel 2010). Consequently, although they share a particular feature that "they incorporate knowledge from more than one field of study" (Weyant *et al*. 1996; p.377), applications of IAMs in existing climate change assessment approaches vary significantly. They are applied in a variety of frameworks, which differ in their scope, the degree of their level of detail, consideration of uncertainty, and underlying decision-making processes (Füssel 2010; Kunreuther *et al*. 2014).

Figure 2.1 shows a simplified conceptual schematic of the climate 'uncertainty loop', highlighting the different scales at which various aspects of the challenges of global climate change operate and are considered in integrated assessment modelling approaches[11]. The figure also maps the three IPCC WG AR5 reports[12], based on their primary focus, onto the climate 'uncertainty loop'. For example, most global IAMs often focus on evaluating climate mitigation policies. There are about 30 global climate policy IAMs as reviewed and compared in the literature (e.g., Weyant *et al*. 1996; Kelly and Kolstad 1998; Stanton *et al*. 2008; Kriegler *et al*. 2015). Some examples of such IAMs include IMAGE and MESSAGE (which are process-based models with considerable physical detail) and DICE, FUND, MERGE, and PAGE (which mainly focus on intertemporal cost-benefit analysis with relatively less physical detail). On the other hand, regional IAMs often focus on climate change impacts and adaptation assessments. Examples of these include AIM, CLIMSAVE, PRIMA, etc. (see Section 2.4.3 for more details). It is worth stating that a comprehensive assessment of climate change issues would require a holistic treatment of impacts/adaptation and mitigation policies in order to better understand the potential future cross-sectoral impacts and evaluate the potential synergies, conflicts and trade-offs between adaptation and mitigation policies across sectors/sub-systems and scales.

[11] Note that the review in this thesis focuses on IA tools and modelling frameworks that focus on climate impacts and adaptation (as shown with the black box in Figure 2.1), and does not include those that focus mainly on mitigation policy assessments.
[12] The Intergovernmental Panel on Climate Change (IPCC) Working Groups' (WG) contribution to the Fifth Assessment Report (AR5).

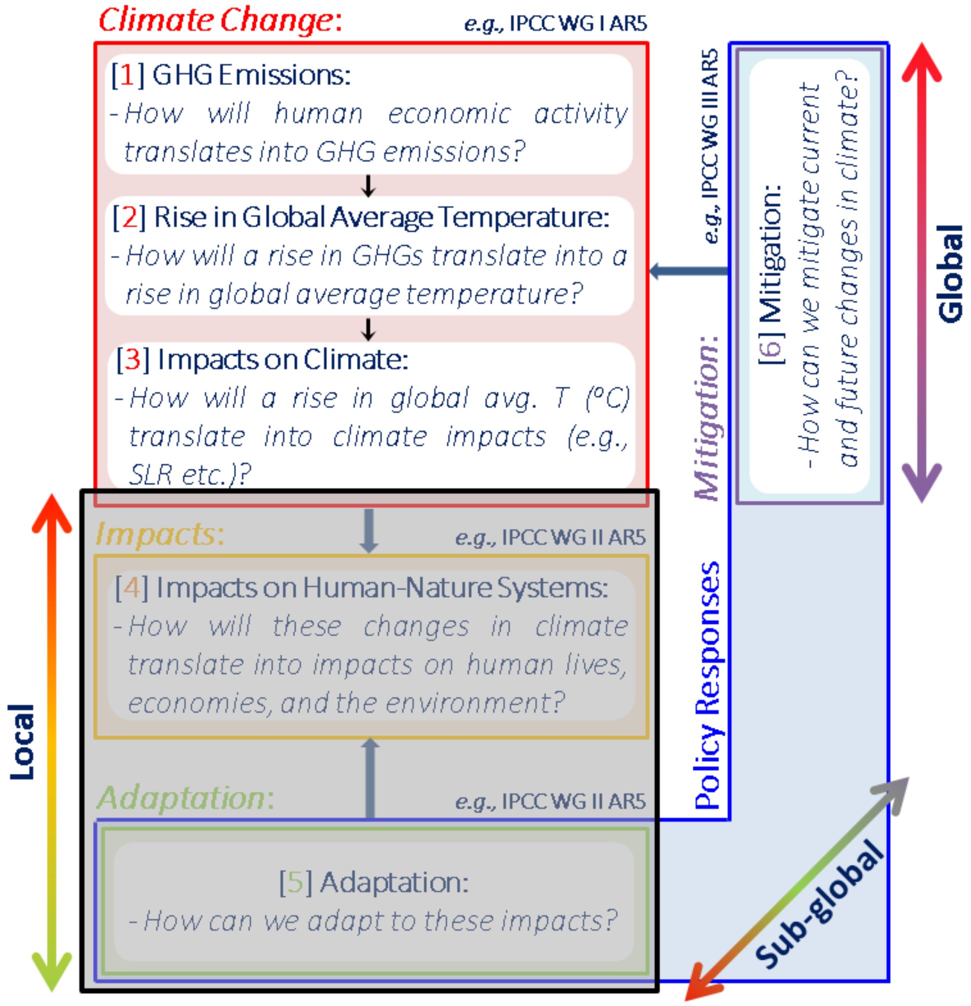


Figure 2.1: *A simplified conceptual schematic diagram of the climate 'uncertainty loop' (adapted from Roberts 2015), and mapping the scales at which its various aspects operate and how the IPCC WG reports are linked to.*

Although there are some overlaps, applications of IAMs can be broadly grouped into three main categories of decision-making analytical frameworks as: (a) *policy optimization* models – which seek to determine the 'best'/'optimal' policy strategies from a large set of 'what-if' exercises, (b) *policy evaluation* models (also known as simulation models) – which assess specific set of alternative policies and examines their consequences in a 'what-if' exercise, and (c) *policy guidance* models – which determine those policies that are compatible with a set of subjectively specified constraints (Weyant *et al*. 1996; Tol 2002; Kriegler and Bruckner 2004; Füssel 2010). The application of (a) and (b) has often focussed on climate change mitigation policies, while there is a growing application of (c) for climate change adaptation policies. Most applications of IAMs for policy optimization and evaluation often try to understand trade-offs between the impacts of climate change and the impacts of greenhouse gas emission reduction. Most of these studies are typically used at a global scale, and the models are often not validated against national data, and hence they often lack necessary detail at regional and country levels. Therefore, interpretation of results of these models for application to country or sub-regional levels needs to be treated with great care. Consequently, their application in informing adaptation policies at scales relevant to decision-making is still limited (e.g., Kraucunas *et al*. 2015).

2.4.2 Key criteria for selecting appropriate integrated assessment models

An important criterion in selection of appropriate IAMs is related to the nature and level of integration (see Section 2.3). Integration can be done across multiple components of a particular sector/sub-system (sector-specific approach) or across multiple sectors/sub-systems (systems-of-systems approach) (e.g., Hall *et al*. 2013). A significant focus has been given in the context of sector-specific applications of IAMs by integrating different components (i.e., sectors/sub-systems) of a particular system. Examples include an integrated assessment of agricultural systems (e.g., van Ittersum *et al*. 2008; Janssen *et al*. 2009; Lazar *et al*. 2015), coastal systems (e.g., Dawson *et al*. 2015; Nicholls *et al*. 2015b,c), and water systems (e.g., Henrichs *et al*. 2002; Lehner *et al*. 2006). However, IA approaches across different sectors/sub-systems at finer than global (e.g., regional) scales for long-term planning of climate change adaptation are challenging and still limited. This is partly because sector-specific models often consider fundamentally different modelling approaches with varying purposes. Hence, one of the key aspects of IAMs in representation of systems of a system lies in the extent of the capacity to characterize interactions of and feedbacks between sub-systems within the target system, while keeping model components and linkages effective but efficient (Jakeman and Letcher 2003).

Another important distinction of IAMs is their consideration of uncertainty. The simplest and most commonly used approach in considering uncertainty is the application of sensitivity analysis by varying parameters, often based on a one at a time approach (Füssel 2010). Other more advanced approaches include: (a) stochastic simulation based on the use of specified probability distributions for uncertain input parameters and assessing the probability distributions of the resulting output parameters, and (b) adaptive analysis based on probabilistic applications of optimizing models to assess key future scientific and policy uncertainties (Füssel 2010). Such approaches, however, raise the issue of complexity limiting the application of IAMs for policy making. Consequently, one of the key criteria in designing IAMs is the consideration of computational efficiency (Sims *et al*. 1997). A policy-oriented assessment tool should allow multiple assessment-runs that can be performed quickly. This will allow a sensitivity analysis of various model inputs and assumptions to explore the full range of uncertainty (e.g., Sims *et al*. 1997). However, many IAMs are often designed to run on desktop computers and the reduced processing power, memory and secondary storage (disc space) of desktop computers is a determinant factor in the selection of spatial and temporal resolutions, of the scientific complexity and level of detail of the model, as well as their capability to allow comprehensive sensitivity analysis (Sims *et al*. 1997). Consequently, despite the increasing capability in computational power, the use of integrated modelling approaches and tools in informing adaptation policies is still limited due to a number of factors, including unacceptably long model run time (e.g., restricting rapid simulation and interactive engagement of stakeholders with the models) as well as limited accessibility of models for end users (e.g., commercial and/or PC-based nature).

Based on a comprehensive review of the literature on existing systems integration and integrated modelling frameworks, a number of factors have been identified as important criteria for selecting (or to consider when developing) appropriate IAMs that are relevant for climate change impacts and adaptation assessment to inform policy and decision-making processes at appropriate scales. These factors include:

(1) Sectors/sub-systems (number and type) integrated and metrics/indicators considered (e.g., biophysical, social-economic, environmental metrics and their relevance to stakeholders and adaptation) (e.g., agriculture, water, energy, land, etc.),

(2) Type of modelling methods/approaches used such as integration modelling or soft/hard linking of models or aggregation of results (e.g., through data sharing between sectoral experts) (e.g., KBM, ABM, BN, SD, multi-model coupling, etc.),

(3) Type and nature of integration (multiple sectors/sub-systems, issues, disciplines, stakeholders, scales, processes/models integrated, etc.),

(4) Treatment of climate and socio-economic drivers (specific focus, independent/isolated, or holistically),

(5) Treatment of adaptation (e.g., implicit or explicit),

(6) Level of spatio-temporal detail and data availability and requirement (e.g., scale issues across sectors/sub-systems),

(7) Computational considerations and model run time (e.g., level of complexity and issues of model validation),

(8) Treatment of uncertainty and capability for supporting sensitivity analysis, and

(9) Nature/type of the integrated model (web-based or PC-based) and availability to end users (e.g., free or commercial),

(10) Level of assistance (and training) required to use the final model/tool (e.g., is it user-friendly for stakeholders and policy makers?) and its relevance in adaptation policy decision support.

2.4.3 Comparison of selected integrated assessment modelling approaches and tools

Following the above factors/criteria, a number of IA approaches and tools have been identified in the literature (Appendix A). The review was based on a regional/continental scale integrated climate change impacts and adaptation assessments, including national scale assessments for large countries such as the USA, Canada, China and Australia. In addition, for the purpose of this study, the IAMs included in the review are focussed on those that fully focus on or at least partly include both 'impacts' and 'adaptation' assessment modules (Figure 2.1), as well as availability of detailed information (e.g., publications) regarding the tools. Hence, those integrated assessment studies that solely focus on assessment of mitigation policies only or there is limited freely available detailed information are not included. Selected national (sub-national) and global scale integrated assessments are also included for comparison purposes. Such comparisons allow evaluating the potential for down-/up-scaling of modelling approaches and the lessons that can be learned for future improvements in regional IAM applications.

Fifteen IAMs are identified: **Global scale**: (1) DIVA (*Dynamic Interactive Vulnerability Assessment*), (2) ISI-MIP (*Inter-Sectoral Impact Model Intercomparison Project*), and (3) SimCLIM (*A software modelling system for simulating bio-physical and socio-economic effects of climate variability and change*). **Regional/Continental scale**: (1) ACACIA (*A Concerted Action towards a comprehensive Climate Impacts and Adaptations assessment for the European Union*), (2) ACCELERATES (*Assessing Climate Change Effects on Land use and Ecosystems: from Regional Analysis to the European Scale*), (3) AIM (*The Asia-Pacific Integrated Model*), (4) CLIMSAVE (*CLimate change Integrated assessment Methodology for cross-Sectoral Adaptation and Vulnerability in Europe*), (5) IAM (*Integrated Assessment Model for the Conterminous USA*), (6) IAM (*Integrated Assessment Model for Agriculture in China*), (7) PESETA (*Projection of Economic impact of climate change in Sectors of the European Union based on boTtom-up Analysis*). **National/Sub-national scale**: (1) ClimAID (*Integrated Assessment for Effective Climate Change Adaptation Strategies in New York State*), (2) CLIMPACTS system (*An integrated model for assessment of the effects of climate change on the New Zealand environment*), (3) PRIMA (*Platform for Regional Integrated Modeling and Analysis*), (4) RegIS (*Regional Impact Simulator*), (5) TaiCCAT (*Taiwan integrated research program on Climate*

Change Adaptation Technology). Detailed descriptions of all the IAMs and their respective advantages and limitations are presented in Appendix A.

The review allowed a comparison between the IAMs based on the list of criteria described above to identify the key advantages and limitations for a continental scale assessment of climate and socio-economic change impacts for assisting cross-sectoral adaptation policy decision-making processes. The review shows that while each IAM has its respective advantages, a number of potential improvements have been identified that can inform developments of the next generation of IAMs (Appendix A). The review also highlighted how the CLIMSAVE integrated methodology advances current knowledge in IAM applications in a number of ways. The key strengths of the CLIMSAVE IAP include: (i) improved detail in consideration of cross-sectoral linkages and interactions between six key sectors/sub-systems; (ii) holistic treatment of the climate and socio-economic drivers and their highly flexible setup supporting a comprehensive uncertainty and sensitivity analysis to be undertaken; (iii) higher integration of knowledge between stakeholders and scientists based on a new stakeholder integrated research (STIR) approach (Gramberger *et al*. 2015); (iv) explicit treatment of adaptation; (v) being an accessible web-based tool available freely, and associated user-friendly nature of its user interface to use without requiring any major training.

One of the key factors in IAMs is the level of integration and the balance between appropriate representation of the sectoral interactions and model complexity. While most IAMs are based on soft-linking of component models with relatively loose representation of the cross-sectoral interactions (e.g., ACACIA, ACCELERATES, ISI-MIP, PESETA), those which use hard-linking (e.g., AIM, CLIMPACTS) or fully-integrated (e.g., SimCLIM) often are data intensive and complex, limiting their wider application. However, for SimCLIM its 'open framework' provides a useful flexibility for customisation, although its PC-based and commercial nature limits its wider use and application. The CLIMSAVE approach uses multi-model coupling framework based on emulation (meta-modelling) approach to integrate six different sectors/sub-systems to achieve this. Another important criterion is the treatment of climatic and non-climatic drivers. Most IAMs focus either on one of them only or when considering both to treat them independently or by rigidly combining them using limited number of scenarios. CLIMSAVE, on the other hand, provides a high level of flexibility to allow users to explore the space of plausible alternative futures by considering either independently or holistically (combining them) based on multiple scenario realizations. Moreover, while all the IAMs reviewed are PC-based software, the web-based nature of CLIMSAVE also offers free accessibility to end users and encourages its wider applications. This is crucial as there is a rapidly growing move and interest by stakeholders and decision-makers towards web-based integrated impacts and adaptation assessment tools. This is being considered as a means of enabling and empowering adaptation actions through sharing of information and knowledge and thereby increasing the visibility and understanding of adaptation (e.g., CIRCLE2 Policy Brief). A detailed description of the CLIMSAVE approach and the key aspects of its integrated methodology are presented in detail in Chapter 3. The current limitations (potential future improvements) are also identified and discussed in Section 7.4.

2.5 Long-Term Adaptation Planning: The Need for a Nexus Approach

Adaptation practices are constrained by a wide range of factors, and these will become much more difficult under a changing climate with uncertainty (IPCC 2014). The two main factors affecting climate change adaptation include: (1) the inherent uncertainties in the predictability of both future climate and socio-economic drivers and their potential impacts; and (2) the variability in the methods and assumptions used by any single study to assess potential impacts (e.g., Rosenmund 2012). Thus, not only is our knowledge of the future necessarily uncertain, but also the degree of uncertainty varies considerably. Hence, although the volume of research on adaptation is growing, the challenge in providing suitable information to adequately inform policy-makers for designing robust adaptation strategies still remains (Laves *et al*. 2014). Further, the literature on cross-sectoral adaptation policy integrations success remains scarce (Serrao-Neumann *et al*. 2014). Serrao-Neumann *et al*. (2014) highlighted the key importance of applied cross-sectoral climate adaptation policy integration using a 'learning-by-doing' (developing theoretical knowledge from practice) and 'doing-by-learning' (developing practical knowledge from theory) approaches for developing cross-sectoral adaptation options through extensive collaboration with stakeholders.

Traditionally, adaptation studies have focussed on the analysis of specific risks under climate change scenarios. There are two dominant approaches to climate risk assessment and adaptation studies: 'Top-down' approaches, which feed downscaled climate scenarios into impact models in order to calculate probable impacts and test potential adaptation measures; and 'bottom-up' approaches, which generally focus on ways to reduce the vulnerability of a community to climate events based on past experiences, often following an extreme event or disaster (Wilby and Dessai 2010). However, the effectiveness of adaptation policies in one sector/sub-system can be compromised or aided by policies developed in another sector/sub-system (e.g., Henle *et al*. 2008; Taylor and McAllister 2014). Hence, future adaptation requires a cross-sectoral perspective taking into account interlinked facets of stakeholder engagement, cross-sectoral analysis and policy integration (McAllister *et al*. 2014; Serrao-Neumann *et al*. 2014). These show that climate change adaptation policy-makers need to explicitly consider broader drivers of land-use change and economic adjustment that are likely to impact on proposed adaptations across different sectors/sub-systems and regions (Taylor and McAllister 2014).

Current climate change adaptation practice has a stronger focus on reacting to past events as well as sector-specific policies, rather than on preparing for future climate change with cross-sectoral focus and integrating it with economic and societal development and future mitigation policies (IPCC 2014). However, adaptation is a complex, multi-dimensional phenomenon, with a breadth and depth that cannot be fully covered by the current portfolio of sectoral assessment tools. Hence, future assessments should consider a systematic strategy that takes into account the following two key paths: (1) to find new ways to use the range of existing assessment tools as efficiently and effectively as possible, but at the same time (2) develop building blocks to support the next generation of IA tools. For example, the CLIMSAVE integrated methodology in this regard plays an important role by (1) using and integrating existing sectoral knowledge (e.g., development of meta-models from existing detailed and complex sectoral models) and (2) providing a broader knowledge of the complex interaction between multiple sectors/sub-systems at a European scale. As such, future climate change impacts and adaptation assessments should take into account the cross-sectoral nature of impacts and associated trade-offs and synergies/conflicts between different sectoral adaptation strategies (e.g., Berry *et al*. 2015). Hoff (2011) also highlighted that continuing with the 'business as usual' is no longer an option. There is a need for a nexus approach – an approach that integrates management and governance across sectors/sub-systems and scales. Adaptation planning based on such an approach increases efficiency, reduces trade-offs, builds synergies, and improves governance across sectors/sub-systems.

3. THE CLIMSAVE INTEGRATED APPROACH: A EUROPEAN ANALYSIS

3.1 The CLIMSAVE Integrated Framework

CLIMSAVE is a pan-European research project (from Jan 2010 to Oct 2013) funded under the EU FP7 programme. The project is coordinated by the Environmental Change Institute (University of Oxford). The consortium involves 18 partner institutions from 13 different countries in Europe as well as from China and Australia. The overall aim of the CLIMSAVE project is to deliver a European level IA methodology to investigate the cross-sectoral impacts of, and vulnerabilities and adaptation to, a range of climate and non-climate drivers of change in Europe (Harrison *et al*. 2013; 2015b).

To achieve this, a range of sectoral impact models have been developed and integrated within a common web-based assessment platform, by focusing on six key land- and water-based sectors/sub-systems in Europe: agriculture, biodiversity, coasts, forests, urban, and water. The IAP development applies multi-models coupling approach (Section 2.2.3), which involves linking of 10 disparate impact models from the six different sectors/sub-systems to capture the complex interactions and feedbacks between these sectors/sub-systems, including competition for land and water and associated cross-sectoral impacts. Figure 3.1 shows the six sectors/sub-systems integrated and associated interactions considered within the CLIMSAVE project.

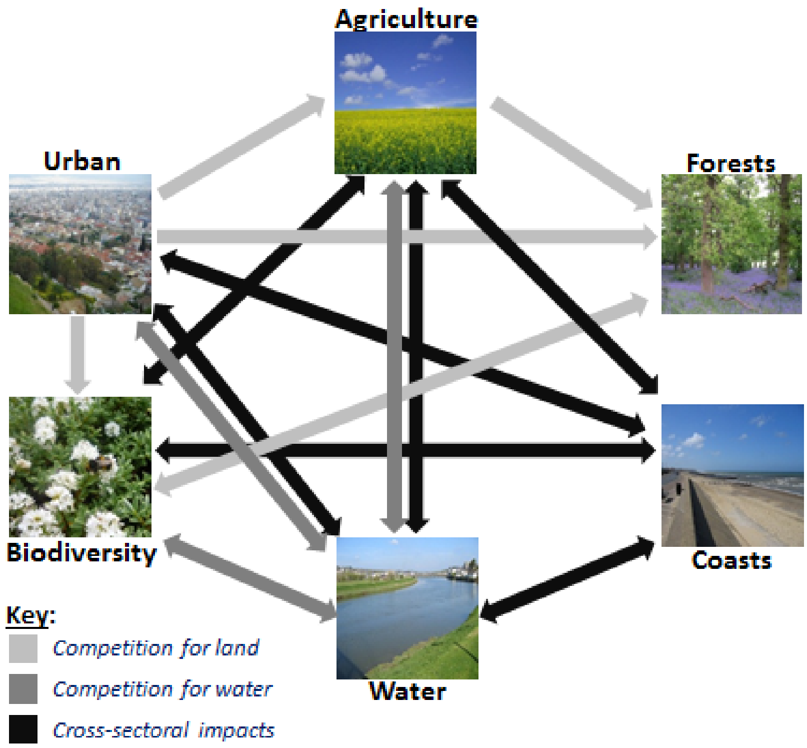


Figure 3.1: *Schematic diagram of the six key sectors/sub-systems and associated interactions considered within the CLIMSAVE IAP.*

The tool is intended to put science in the service of stakeholders and policy-makers by providing a common platform for an improved integrated assessment of impacts, vulnerabilities and related cost-effective adaptation measures for key sectors/sub-systems in Europe. The linking and integration of the different sectoral impact models will allow stakeholders (e.g., academic, governmental, professional, and other interested citizens) to explore and better understand how the interactions between the different sectors/sub-systems could affect the dynamics of future European landscape change, rather than viewing each sector/sub-system and/or their own area in isolation. Hence, it provides important sectoral and cross-sectoral insights by exploring 'what if's' under different climate change as well as policy options that reflect different socio-economic conditions. As such, it provides important information which contributes to the development of a well-adapted Europe by building the capacity of stakeholders and decision-makers. It facilitates a better understanding of the complex issues surrounding climate change impacts and allows exploring appropriate adaption opportunities under uncertain futures for making more reliable choices based on solid scientific knowledge (Harrison *et al*. 2013).

The CLIMSAVE approach uses a stakeholder-integrated participatory scenario development process implemented throughout the project period (Harrison *et al*. 2013). The process involved a systematic and continuous stakeholder engagement and stakeholders having a driving role in: (a) developing and refining the qualitative socio-economic scenarios, the possible adaptation options, and the associated links, and (b) interacting and testing of the IAP to provide feedback on the design and functionality of the user interface. To achieve these, the project involved a series of six workshops (three for Europe and three for Scotland studies) which were used to integrate stakeholder views into the climate change impacts, vulnerability and adaptation assessment research. This allowed a two-way exchange of information between stakeholders and scientists and insured that stakeholders' perspectives are an intrinsic part of the resulting socio-economic scenarios and associated adaptation options that are integrated within the CLIMSAVE IAP (Harrison *et al*. 2013).

3.2 The Integrated Assessment Platform (IAP)

The CLIMSAVE IAP is a unique user-friendly and interactive exploratory web-based integrated landscape change assessment tool. It provides an integrated methodology intended to assist stakeholders and decision-makers in developing their capacity to improve their understanding about the complex challenges surrounding cross-sectoral impacts, vulnerability and adaptation responses due to future climate and socio-economic change under uncertain futures. It also allows stakeholders and researchers to explore how climate change will interact with changing social, economic and political conditions in the future and that all these factors need to be considered to assess the robustness of cross-sectoral adaptation responses.

The key aspects of the CLIMSAVE IAP lies in its holistic methodology framework which improves on previous studies in five important ways: (i) higher integration of knowledge from stakeholders and scientists, (ii) greater considerations of important cross-sectoral linkages/interactions and feedbacks by integrating six different key sectors/sub-systems (agriculture, biodiversity, coasts, forestry, urban areas, and water resources), (iii) holistic consideration of the combined effects of both climatic and socio-economic factors, (iv) multi-scale applications (continental scale: Europe and regional scale: Scotland), and (v) providing a freely accessible and user friendly web-based platform. However, it is worth stating that the IAP is intended to complement, rather than replace, the use of more detailed sectoral tools in informing the development of robust adaptation policy responses. The European scale IAP operates at a 10’ long. x 10’ lat. grid resolution (i.e., with a total of 23,871 grid cells in Europe), while the regional scale IAP developed for Scotland operates at a 5 km x 5 km grid resolution (i.e., with a total of 3,472 grid cells in Scotland). Here, only application of the European scale IAP is considered.

The CLIMSAVE IAP uses *meta-modelling* approach which allowed integration of various sectoral impact assessment models to provide stakeholders with an interactive assessment tool with reasonably fast model run-times and appropriate functionality (Holman *et al*. 2008a,b; Holman and Harrison 2012). Meta-models (also termed as ‘reduced-form models’) are computationally simple(r) but efficient modelling techniques that emulate the performance of more complex models (Ratto *et al*. 2012). A variety of meta-modelling techniques are used to abstract sufficient representation of the key interactions and feedbacks for inclusion within the IAP. Examples of the meta-modelling techniques used in the platform include *look-up tables*, *artificial neural networks (ANNs)*, *soil/climate clustering*, and *3D surface response diagrams*. Hence, the IAP contains the series of inter-linked meta-models (i.e., the ten disparate sectoral impact meta-models that are implemented as *Dynamic Link Libraries*, DLLs), an internal database (e.g., elevation data), a wide range of climate and socio-economic scenarios, and a GIS-based user interface that captures the interactions and feedbacks between different sectors/sub-systems. Each sectoral meta-model is developed using different modelling approaches with a focus on fast run-times and computational efficiency (detailed description of the approaches used for each meta-model is available in Holman and Harrison (2012)). Each meta-model is designed to be modular, independent, and capable of replacement at any time. This allows efficient integration and development of the IAP as well as providing flexibility in future development by integrating new knowledge and data as it emerges. Figure 3.2 shows a schematic flow diagram of the sectoral impact meta-models and associated linkages/interactions integrated within the IAP. The various models' interactions, the interface, and associated data flows within the IAP are handled by a Running Module. Hence, one integrated simulation of the IAP involves the following five key components of data readings and exchanges between the various models, databases, and user selections (through the platform interface) (see Holman and Cojocaru 2012):

(1) from the user to the sectoral models, representing the communication of input parameter values from the user (e.g., slider bars, timeslice, scenarios, etc.) to the models, via the Running Module,
(2) between the sectoral models, where a simulated output from one sectoral model is an input to other sectoral models,
(3) between the sectoral models and the user Interface, as outputs are selected by the user for display,
(4) from the IAP Database to the sectoral models containing, for example, the input data for a user-selected scenario, and
(5) data that is read into a sectoral model from the model's own internal dataset.

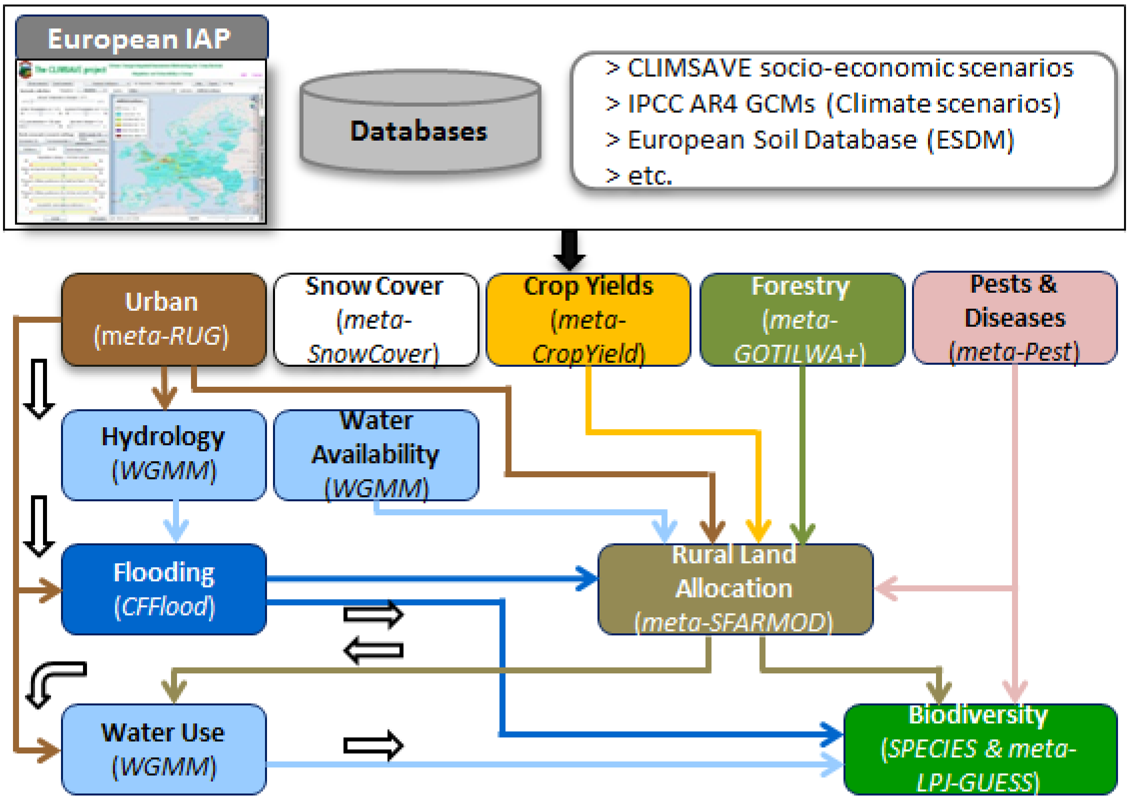


Figure 3.2: *Schematic of the various sectoral meta-model (shown in brackets) linkages and associated data flows integrated within the CLIMSAVE European IAP (Adapted from Harrison et al. 2013).*

3.3 The IAP Sectoral Models

The following sub-sections present brief descriptions of the various sectoral meta-models integrated within the European IAP (see Holman and Harrison 2012 for more details).

3.3.1 Urban: The RUG meta-model

The RUG (Regional Urban Growth) meta-model uses a look-up table based meta-modelling approach based on the original RUG model (see Reginster and Rounsevell 2006; Rickebusch 2010). The meta-model simulates urban growth as a function of changes in socio-economic variables (e.g., population, GDP per capita) and societal values (e.g., strictness of planning constraints to limit sprawl, household preferences for proximity to green space/social amenities, attractiveness of the coast in terms of scenic value/flood risk) (Holman and Harrison 2012). The meta-model also takes into account local geography, travel times with the existing infrastructure and city typology (e.g., monocentric vs polycentric). It consists of look-up tables of the proportion of artificial surfaces per 10'x10' grid cell aggregated from the original RUG model runs (on a 1x1 km grid) considering all the possible combinations of the IAP input values. The original RUG model calculates the proportion of artificial surfaces based on a linear regression modelling approach, which runs on a 'growth-only' assumption, and cannot simulate shrinkage from the baseline. The model was calibrated based on the baseline data, and the differences between the baseline simulation and the observed CORINE land-cover data are on average around 2-3%, with most values less than 7% (Holman and Harrison 2012).

3.3.2 Flooding: The CFFlood meta-model

The CFFlood (Coastal Fluvial Flood) meta-model is a simplified process-based model developed based on experience from previous models: RegIS2 (Regional Impact Simulator; Mokrech *et al*. 2008; Richards *et al*. 2008) and DIVA (Dynamic Interactive Vulnerability Assessment; Vafeidis *et al*. 2008; McFadden *et al*. 2007). The meta-model consists of three coupled sub-model components, including: (1) Coastal flood, (2) Fluvial flood, and (3) Habitat change/loss (see Mokrech *et al*. 2015 for detailed descriptions). The CFFlood model is a 2-dimensional model which provides estimates of the socio-economic (e.g., people flooded and economic damages) and environmental (e.g., floodplain habitats loss/change) impacts of both coastal and fluvial flooding due to future changes in climatic and socio-economic factors. The model identifies the area at risk of flooding based on topography, relative sea-level rise or change in peak river flow, and estimated Standard of Protection of flood defences. An estimate of the people living in the flood risk zones is calculated using population density. The flood damages (both contents and structure) for residential and non-residential properties are calculated based on urban areas, people at risk of flooding, flood water depths, and Gross Domestic Product (GDP). The CFFlood model assesses possible changes in the area of coastal floodplain habitats based on accommodation space, sediment supply and the ratio of relative sea-level rise to tidal range. The meta-model also allows exploring the benefits of various adaptation measures to reduce risks of flooding and minimising loss of important floodplain habitats.

3.3.3 Agriculture: The SFARMOD, CropYield, Pests, and SnowCover meta-models

The SFARMOD meta-model uses soil/climate clustering meta-modelling approach combined with ANNs (see Audsley *et al*. 2006; 2015). It is based on the full original SFARMOD-LP mechanistic farm-based optimizing linear programme model of long-term strategic agricultural land use (Annetts and Audsley 2002; Holman *et al*. 2005b). The meta-model simulates the behaviour of the full SFARMOD-LP model, using its outputs from 20,000 randomly selected sets of input data that fully cover the parameter input space. The rural land allocation modelling approach is based on a series of regression equations that estimates "first the percentage of the area of each crop, then the costs of dairy cows (concentrates[13]) then the fixed costs of labour and machinery and finally the profitability of this element" (Audsley *et al*. 2015; p.221). Up to 10 iterations based on profitability and food demand are allowed to determine the final land allocation and food production based on selected thresholds. The model uses a concept of profitability where, if the profit is: (i) above a first threshold, the land will be allocated as intensive (i.e., either arable or grassland/diary cropping); (ii) above a second threshold then land is allocated as extensive grassland; or (iii) below the second threshold then land is considered as abandoned (i.e., forest or bare rock that is unusable for agriculture). The SFARMOD meta-model had a <5% misclassification compared to the full SFARMOD-LP model.

The crop yield meta-models use soil/climate clustering combined with ANNs based on the full agricultural model ROIMPEL (see Rounsevell *et al*. 2003; Audsley *et al*. 2006; 2008). The ANNs are combined with temperature thresholds to prevent crops growing in unsuitable territories. The ANNs for each of the 12 crops (*winter and spring wheat, winter and spring barley, winter oil seed rape, potatoes, grain maize, sunflower, soybean, cotton, grass, and olives*) were calibrated on a training set of data from simulated outputs of the original ROIMPEL model using datasets including more than 150,000 data points. The training and validation datasets were sampled (considering both input/output values outside the ± 1 standard deviation from the mean of each parameter) to adequately cover the whole range of both soil and climate predictors and the predicted variables (such as sowing date or actual yield). Overall the root-mean-square error (RMSE) is in most cases below 0.5 t/ha, with the mean biased error (MBE)

[13] Dairy feeds, which can be broadly divided into two categories as sources of: (i) energy and (ii) protein.

also estimated approximately equal to 0 indicating that there is low/no systematic bias (see Audsley *et al*. 2015).

The pest meta-models also uses ANNs based on the outputs of the climate-matching software program CLIMEX, which estimates species' geographical distribution by taking into account the climate conditions of a given location (Holman and Harrison 2012). CLIMEX assumes that the suitability of a climate for a given species can be predicted from the knowledge of its current area of occurrence, by mimicking the mechanisms that limit the geographical distributions of a species to determine their seasonal phenology (Sutherst *et al*. 2004). The meta-model considers seven pest species, namely: *Ostrinia nubilalis, Leptinotarsa decemlineata, Cydia pomonella, Lobesia botrana, Oulema melanopus, Rhopalosiphum padi and Sitobion avenae*.

The snow cover meta-model is based on ANNs, which were trained and validated based on outputs from the original and more detailed SnowMAUS snow cover simulator (Trnka *et al*. 2010). The calibration is made using a training set of data from simulated outputs of SnowMAUS that are sampled to cover the wide range of predictors and the predicted variable (i.e., the number of days with snow). SnowMAUS operates on a daily time step, with seven key parameters that govern snow accumulation and melting (Holman and Harrison 2012). Snow melting is usually facilitated by other factors, such as sublimation, sun-driven ablation and often combined with the influence of wind.

3.3.4 Forest: The metaGOTILWA+ model

The metaGOTILWA+ model is based on ANNs and simulates the impacts of climate change on forest ecosystems services (e.g., wood production, wood balance) and the benefits of forest management as mitigation measures to reduce impacts on five main forest species[14] in Europe (Holman and Harrison 2012). The meta-model emulates the performance of the original GOTILWA+ (Growth Of Trees Is Limited by WAter) model (Morales *et al*. 2005; Schröter *et al*. 2005). It was trained using GOTILWA+ simulated outputs for 889 selected sample cells which spanned the range of environmental conditions of five regions across Europe (i.e., *Alpine, Atlantic, Boreal, Continental, Mediterranean*). For each cell, GOTILWA+ simulations were conducted for all combinations of a range of characteristic tree species, three different management regimes and with four different levels of effective soil volume. The predictions of the ANN were tested against GOTILWA+ data from cells which were not used for training and a strong 1:1 relationship is found between the meta-model and the original GOTILWA+ model,

[14] The five representative European tree species considered are: (1) *Pinus sylvestris,* (2) *Pinus halepensis,* (3) *Pinus pinaster,* (4) *Quercus ilex,* & (5) *Fagus sylvatica*.

with r^2 values for meta-model indicators all greater than 0.9. The model is also discussed in Audsley *et al*. (2015).

3.3.5 Water: The WaterGAP meta-model

The WaterGAP meta-model (WGMM) assesses the impacts of global changes on water resources and use in Europe under a range of climate and socio-economic scenarios. The meta-model uses look-up tables to emulate the performance and reproduce the outputs of the original WaterGAP3 (Water-Global Assessment and Prognosis) model (Alcamo *et al*. 2003; Döll *et al*. 2003). The original model uses a 5'x5' spatial resolution (with over 180,000 grid cells for Europe). In order to reduce model run times and input data requirements, the meta-model aggregates the grids into 95 spatial units (i.e., European river basins larger than 10,000 km^2, where each basin represents single large river basins or clusters of smaller, neighbouring river basins with similar hydro-geographic properties) (Wimmer *et al*. 2015). The meta-model representation uses 3-dimensional response surfaces to river basins derived from outputs of the original model to relate changes in water availability with simultaneously changed mean temperature and precipitation. Under a changed climate, the relative deviation of the average river discharge simulated by WGMM from aggregated WaterGAP3 output is estimated between ±5% for most of Europe. The water use outputs of the meta-model for the domestic, manufacturing, and thermal electricity production sectors/sub-systems also shows a very good match with the WaterGAP3 results, with R^2 estimated at 0.975 for the domestic/thermal electricity production and 0.998 for manufacturing (Wimmer *et al*. 2015).

3.3.6 Biodiversity: The LPJ-GUESS and SPECIES meta-models

The LPJ-GUESS meta-model uses look-up tables based on the original LPJ-GUESS model (see Sallaba *et al*. 2015). LPJ-GUESS is a complex dynamic global vegetation model, which uses a process-orientated ecosystem modelling framework (Sitch *et al*. 2003). The meta-model is developed based on simulations from the original model consisting a subset of 63 grid cells (of 0.5^{o}x0.5^{o} spatial resolution) situated along two cross European transects to capture north to south-west and north-west to south-east climatic transitions. The model considers temperature, winter and summer precipitation and atmospheric CO_2 concentrations as the key input drivers, while the main output ecosystem parameters include net primary production (NPP), leaf area index (LAI) and aboveground carbon mass (C_{mass}). The results of the meta-model were calibrated and validated using outputs from the original model, defining NPP ratio (between that of the meta-model and the original model) of 0.9–1.1 (which assumes an error of ±10%) (Sallaba *et al*. 2015).

The SPECIES meta-model uses ANNs (Holman and Harrison 2012) based on the original SPECIES (Spatial Estimator of the Climate Impacts on the Envelope of Species) model (Pearson *et al*. 2002; Harrison *et al*. 2006). It simulates the suitable climate space of more than 100 species selected to interact with other sectors/sub-systems such as agriculture, forestry, coastal and water, and to indicate a range of associated ecosystem services. The model is based on ensembles of ANNs. It incorporates bioclimatic (climate and soil moisture) variables to characterise bioclimatic suitability envelopes for providing projections of species' distributions. "The meta-model is trained using existing empirical data on the European and North African (north of 15^{o}N) distributions of species to enable the full climate space of a species to be characterised" (Holman and Harrison 2012; p.104). The models are trained and validated for 111 species using an ensemble forecasting approach. The results demonstrate that all species "show AUC[15] statistics greater than 0.8, indicating good discrimination ability and 84% has AUC statistics greater than 0.9, indicating excellent model performance" (p.106). In addition, kappa values greater than 0.7 were estimated for over 45% of the species. This is considered as "very good agreement between simulated and observed distributions" (Holman and Harrison 2012; p.106).

3.4 The IAP User Interface

The CLIMSAVE IAP user interface contains four assessment screens designed to facilitate a two-way iterative process of dialogue and explorations of 'what if's' under various plausible futures. These screens are:

(1) ***Impact*** screen: allows investigating how different amounts of future climate and socio-economic change may affect urban, rural and coastal areas, agriculture, forestry, water, and biodiversity sectors/sub-systems.

(2) ***Vulnerability*** screen: allows identifying which areas or 'hot spots' in Europe are vulnerable to climate change under the socio-economic scenarios being considered by the user, before and/or after adaptation.

(3) ***Adaptation*** screen: allows investigating how adaptation can reduce the impacts of climate change across Europe, within the constraints of the socio-economic scenario selected by the user.

(4) ***Cost-Effectiveness*** screen: allows identifying which adaptation measures will most cost-effectively reduce the impacts of climate change. It allows evaluating the relative cost-

[15] Area Under the Receiver Operating Characteristic (RUC) Curve. RUC Curve is a graphical illustration of the statistical performance of a binary classification system based on variation of its discrimination threshold (e.g., Hanley and McNeil 1982).

effectiveness of the various individual adaptation measures selected in the 'Adaptation' screen.

The user can move through the different screens of the platform in a number of ways for assessing cross-sectoral impacts and vulnerabilities (with or without adaptation) as well as cost-effectiveness of the adaptation options, by looking at, for example: (a) impacts only (potential impacts), (b) impacts and adaptation (residual impacts), (c) vulnerability before and after adaptation, and (d) effectiveness of adaptation costs (Figure 3.3).

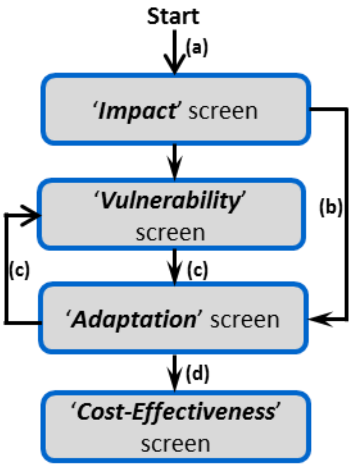


Figure 3.3: *A simplified flow chart of the different alternative pathways through the CLIMSAVE IAP which are available for user selection (Adapted from Holman et al. 2013).*

Figure 3.4 illustrates the key options (including timeslice, scenario, sector/sub-system, and impact indicator selections) within the user interface based on examples of functionalities in the 'Impact' screen of the IAP.

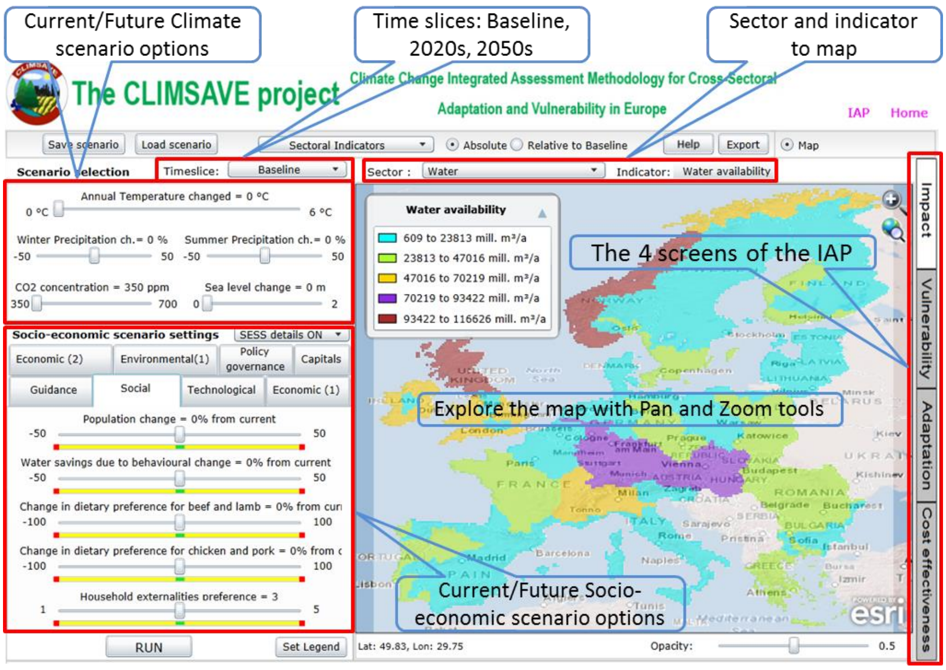


Figure 3.4: *The European CLIMSAVE IAP showing the 'Impact' screen and the key components of the various additional options available for user selection.*

3.5 The Climate and Socio-Economic Change Drivers and Future Scenarios

A wide range of factors can lead to a direct or indirect effect on well-being of the human society and health of the natural systems. Many of these changes are intended or unintended consequences of human decisions and associated actions. Some of the drivers of such changes may be well understood and defined, while others may also involve more complex and diffuse interactions associated with factors such as institutional or cultural influences. According to the Millennium Ecosystem Assessment, a *driver* is defined as "any natural or human-induced factor that directly or indirectly causes a change in an ecosystem" (Nelson *et al*. 2005; p.175). Understanding these driving factors which cause such changes in ecosystem goods and services is an essential part of the challenge in order to design appropriate interventions that maximise the positive and minimise negative impacts of future changes. The CLIMSAVE project considers two main classes of environmental change drivers, including those reflecting climatic change drivers and those representing socio-economic change driving factors and processes (including social, technological, economic, political, etc.). These drivers are identified based on their relevance to stakeholders and adaptation responses. Table 3.1 presents a complete list of the input drivers (representing 5 climatic and 22 socio-economic factors) incorporated within the CLIMSAVE IAP.

Table 3.1: *Lists and description of the various climate and socio-economic change drivers integrated within the CLIMSAVE IAP.*

Climate Change Drivers
<u>**Climate**</u>: 1. Annual temperature change: *Change in mean annual temperature (^oC) relative to 1961-90 baseline.* 2. Winter precipitation change: *Change in precipitation (%) for the winter half-year (October to March) relative to 1961-90 baseline.* 3. Summer precipitation change: *Change in precipitation (%) for the summer half-year (April to September) relative to 1961-90 baseline.* 4. CO_2 concentration: *Change (ppm) in atmospheric CO_2 concentration.* 5. Sea-level change: *Change in mean sea level in North West Atlantic (m) relative to 1961-90 baseline.*
Socio-Economic Change Drivers
<u>**Social**</u>: 6. Population change: *Change in population, in % from current value.* 7. Water savings due to behavioural change: *Reflects water savings due to behavioural change to use less water, in % from current (negative values imply increasing water use due to more water-intensive behaviour).* 8. Change in dietary preference for beef and lamb: *Reflects the change (in % from current) in preference and demand for largely grass-fed meat.* 9. Change in dietary preference for chicken and pork: *Reflects the change (in % from current) in preference and demand for largely grain-fed meat.* 10. Household externalities preference: *Reflects people's relative desire to live in rural areas with access to green space (1) or urban areas with access to social facilities/amenities (5).* <u>**Economic**</u>: 11. GDP change: *Change (%) in Gross Domestic Product, relative to 2010.*

12. Change in oil price: *Change (%) in oil price, relative to 2010.*
13. Change in bioenergy production: *Represents more land allocated to agricultural bioenergy and biomass crops (and so less for food and nature) or vice versa; it is* additional % of arable land devoted for bioenergy.
14. Change in food imports: *Change (%) in food imports, relative to 2010.*

Environmental:

15. Set-aside: *Proportion (%) of arable land set-aside for biodiversity.*
16. Reducing diffuse source of pollution from irrigation: *Reducing crop inputs, such as fertiliser N and pesticides.*
17. Coastal flood event: *The coastal flood event return period for which flooding impacts are calculated.*
18. Fluvial flood event: *The fluvial flood event return period for which flooding impacts are calculated*
19. Forest management: *Dominant forest management approach for 5 main tree species: optimum, even-aged (clearfelling and re-planting to give uniform age distribution) or uneven-aged (patch cutting and planting to produce age distribution)*.

Technological:

20. Change in agricultural mechanisation: *Change (as % from current) in the amount of labour-saving mechanisation.*
21. Water savings due to technological change: *Water savings (as % from current) in domestic and industrial water demand due to technological improvements (negative values imply more water-intensive technologies).*
22. Change in agricultural yields: *Changes (as % from current) in crop yields due to plant breeding and agronomy (leading to increases) or environmental priorities (leading to decreases).*
23. Change in irrigation efficiency: *Change (as % from current) in the amount of water used to produce a fixed amount of food.*

Policy Governance:

24. Compact vs sprawled development: *Planning policy to control urban expansion, and so protect land availability for food and biodiversity through, for example, planning restrictions and requirements, tax measures.*
25. Attractiveness of coast: *Preference for living at the coast.*
26. Water demand prioritization: *How water should be prioritised when demand is greater than availability (giving priority to food production, environmental needs or domestic/industrial needs).*
27. Level of flood protection: *The standard of protection of flood defences. No flood protection – exploratory option that assumes there are no flood defences in place, Minimum represents indicative estimates of flood protection based on land use/land cover and available flood protection data (lower range = default option); and Maximum represents indicative estimate of flood protection based on land use/land cover and available flood protection data (upper range).*

Climate change impact assessments cannot ignore concurrent changes in socio-economics, as these changes define the context of climate change and may increase or reduce the impacts of climate change (Carter *et al*. 2001). Given the long time horizon of climate change and the challenges in predicting even short-term socio-economic changes, scenarios characterising different futures of the world represent one of the most widely used tools in climate change analyses. Hence, climate change impact assessments require the development of coherent and internally consistent scenarios of future climate and socio-economic changes. They represent pictures of plausible alternative futures that capture future development directions in complex systems that often are either naturally unpredictable or insufficiently understood or are highly scientifically uncertain (Carter *et al*. 2001).

Scenarios help stakeholders and decision-makers to better understand the different ways in which the future might develop and can be used to evaluate and change current thinking and, thus, improve future decision-making (Harrison *et al*. 2013). Scenarios can also be used to integrate knowledge and enhance 'out of the box' thinking across expertise (stakeholders versus researchers), across disciplines (areas of expertise within a project consortium), and across a wide range of factors, sectors/sub-systems, and actors (Kok *et al*. 2015). In CLIMSAVE, the climatic scenarios were identified based on existing IPCC-AR4 scenarios, while the socio-economic scenarios were developed within the project (Dubrovsky *et al*. 2013). These scenarios are integrated within the IAP and can be selected either independently or in combination for two future time-slices (i.e., 2020s or 2050s). The high level of flexibility in scenario selection within the IAP allows exploration of how impacts and cross-sectoral interactions change for different scenario combinations, including change in climate drivers only, or socio-economic drivers only, or both climate and socio-economic drivers combined. The following sub-sections provide brief descriptions of the CLIMSAVE climate and socio-economic scenarios that are integrated within the European IAP.

3.5.1 *Climate change drivers and future scenarios*

The climate change scenarios that are selected and incorporated within the European IAP are based on the IPCC GHG emissions scenarios (SRES A1B, A2, B1 or B2), a range of climate sensitivities (low, medium or high) and a number of global climate models (GCMs) that can be selected by the user. In order to make the number of combinations manageable for the user, outputs from five (i.e., MPEH5, CSMK3, HadGEM, GFCM21 and IPCM4) out of the 16 candidate GCMs (available from the IPCC-AR4 database) are included within the IAP. The GCM selection was done using an objective method developed based on two criteria: (1) quality[16] of GCMs and (2) ability of the GCM subset to represent the inter-GCM variability (see Dubrovsky *et al*. 2015 for further details). For example, projections for temperature change range from 1.1°C (under the B1 emission, Low climate sensitivity, and HadGEM GCM) to 4.9°C (under the A1B emission, High climate sensitivity, CSMK3 GCM) in winter and from 1.0°C (under the B1 emission, Low climate sensitivity, and MPEH5 GCM) to 3.6°C (under the A1B emission, High climate sensitivity, and IPCM4 GCM) in summer in the 2050s. On the other hand, projections for precipitation change range from increases of between 1.1 and 12.5% in winter and decreases of between 2.0 and 29.5% in summer. However, it is worth stating that these are Europe-wide area-average values and the spatial pattern of both temperature and precipitation changes vary according to the GCMs (Dubrovsky *et al*. 2015).

[16] *"…based on the ability of the GCM to reproduce the reference (1961-90) seasonal cycles of temperature and precipitation… dataset*" (Dubrovsky *et al*. 2015; p.174)

3.5.2 Socio-economic change drivers and future scenarios

In addition to the above climate scenarios, the CLIMSAVE IAP also contains a set of four socio-economic scenarios that were developed by European stakeholders in a series of three professionally facilitated, participatory scenario development workshops during the project period (Gramberger *et al*. 2015). The European scenario logic is structured along two dimensions, each representing the two key uncertainties facing Europe, which formed the basis of the scenarios: 'Solutions by Innovation' (effective or ineffective) and 'Economic Development' (gradual or rollercoaster) (Figure 3.5). Within the context of these two dimensions, the four scenarios cover a range of drivers including social and economic developments as well as cultural, institutional and political aspects in a set of integrated future outlooks (Kok *et al*. 2015). The four scenarios cover a wide range of plausible future Europe, with Quadrant I representing the very positive future and Quadrant III representing the very negative future.

Figure 3.5: *The CLIMSAVE European socio-economic scenario logic, with each quadrant representing the respective scenarios (Source: Gramberger et al. 2013).*

Below are brief descriptions of each of the four European socio-economic scenarios:

I. **We are the World**: represents the most prosperous future scenario, combining gradual economic development and high levels of effective solutions by innovation to the depletion of natural resources; where effective governments change the focus from GDP to well-being, which leads to a redistribution of wealth, and thus to less inequality and more (global) cooperation.

II. **Icarus**: is characterised by gradual economic development but ineffective solutions by innovation; and in contrast with the We are the World scenario, governments in this scenario focus on short-term policy planning, which together with a gradually stagnating economy, leads to the disintegration of the social fabric and to a shortage of goods and services.

III. **Should I Stay or Should I Go**: is characterised by a rollercoaster of economic development and ineffective solutions by innovation, with actors failing to address the economic crises, which leads to an increased gap between rich and poor, to political instability and to conflicts.

IV. **Riders on the Storm**: is characterised by effective solutions by innovation but adversely affected by continual rollercoaster of economic crises. However, actors successfully counter this situation by investing in renewable energy and green technologies.

3.6 Summary Overview and Objectives of this Research

As discussed in previous sections, most climate change studies use a scenario approach to assess the potential impacts and adaptation by exploring a selected set of plausible alternative futures. It has been argued that future changes in socio-economic systems have been insufficiently integrated with an analysis of climate change impacts, and that participatory methods of scenario development are the ideal approach for analysing potential changes in the socio-economic systems (e.g., Berkhout *et al*. 2002). Moreover, most impact assessment studies consider a limited (usually four) number of scenarios with a particular focus on the uncertainties of individual (climate and/or socio-economic) drivers rather than considering uncertainty of the possible combination of these drivers representing the scenario space associated with uncertainties of the various key climatic and socio-economic drivers of change. However, such analyses based on only limited number of scenarios may not produce reliable results (PROVIA 2013a), which could potentially under- or over-estimate future adaptation need. This highlights the need for a more comprehensive and multiple scenario analysis to estimate the potential impacts and adaptation. Use of multiple scenarios is in fact a sophisticated sensitivity analysis in terms of exploring the overall uncertainty space, which provides the additional advantage that a better understanding of the system is obtained (PROVIA 2013a).

This research considers an application of the CLIMSAVE IAP using an extensive and systematic sensitivity and scenario analyses (drawing from a combined one-driver-at-a-time (ODAT) sensitivity analysis and multiple-drivers-at-a-time (MDAT) scenario and uncertainty analysis approaches). The study considers an improved representation of the scenario space of the key drivers in order to provide a comprehensive understanding of the overall uncertainties of future cross-sectoral impacts due to various climate change and socio-economic change uncertainties. The research also investigates robustness of different adaptation policy options to better understand the cross-sectoral synergies, trade-offs and conflicts between various sectors/sub-systems under a wide range of adaptation strategies to identify robust adaptation policies in Europe. Detailed descriptions of the material and methods used at different stages of the research are discussed in the following sections.

4. MATERIALS AND METHODOLOGY

4.1 Introduction

This research focusses on an application of the CLIMSAVE European IAP to explore the sensitivities and uncertainties of the cross-sectoral impacts of climate and socio-economic change. The aim is to assess robustness of different adaptation strategies and identify robust cross-sectoral adaptation policies in Europe. The analysis follows a systematic sensitivity and scenario analysis considering a wide range of climate and socio-economic change drivers and scenario combinations. These will explore the space of plausible alternative futures in Europe within the CLIMSAVE IAP. The research will investigate the direct and indirect implications of the combined effects of different climate and socio-economic drivers considering six key land- and water-based sectors/sub-systems in Europe. These include: agriculture, biodiversity, coastal environments, forests, urban areas, and water resources. The study will be based on key impact indicators (one for each sector/sub-system, Table 4.1) selected based on three key criteria: (i) representativeness for the sector/sub-system; (ii) reliability of the IAP in reproducing observed values of the indicators; and (iii) relevance of the indicators to stakeholders.

Figure 4.1 presents a simplified schematic flow diagram of the methodology and the various key steps as part of the three stages of the research, listed below:

(1) Sensitivity analysis: A One-Driver-at-a-Time (ODAT) approach,

(2) Scenario and uncertainty analysis: A Multiple-Drivers-at-a-Time (MDAT) approach, and

(3) Robustness assessment of adaptation policies (RAAP).

A detailed description of each approach is presented in Sections 4.4–4.6.

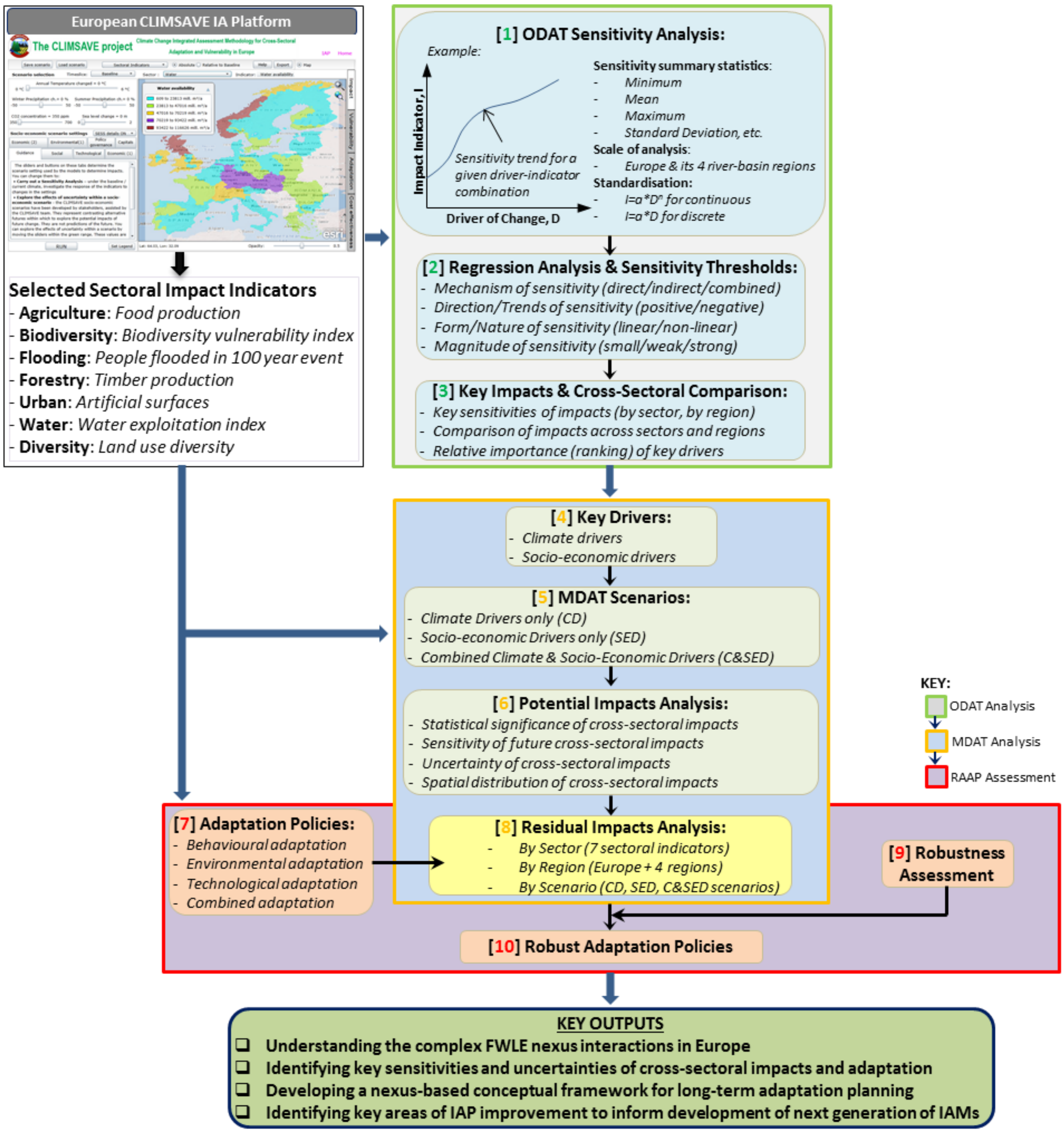


Figure 4.1: *A simplified flowchart summary of the research methodological framework*.

4.2 Study Area and Scale of Analysis

The European IAP operates at a 10 x 10 arc-minutes grid resolution, which produces outputs for a total of 23,871 grid cells. Prior examination of outputs of the IAP highlighted that differential effects of impacts across Europe could be captured by dividing Europe into four regions. Hence, focussing on the cross-sectoral and regional comparison of impacts in Europe, the study analyses the grid-based outputs aggregated into five spatial extents. These are the Europe-wide (EU) extent and its four regions: Eastern Europe (EE), Northern Europe (NE), Western Europe (WE), and Southern Europe (SE). The regional divisions are based on catchment/river basin classifications, rather than country boundaries. The catchment-based regions are selected for a consistent scale of analysis across all sectors/sub-systems. This is necessary as the water sector/sub-system model (i.e., the WGMM meta-model) uses 'river basins' as its modelling spatial unit. These are made up either of a single large river basin or clusters of several smaller, neighbouring basins with similar hydro-geographic properties (Wimmer *et al*. 2015). Some differences between the two regional classifications can be noted in some countries (e.g., France, Germany, Slovakia, and Hungary) that are split between regions by cross-border catchments (Figure 4.2).

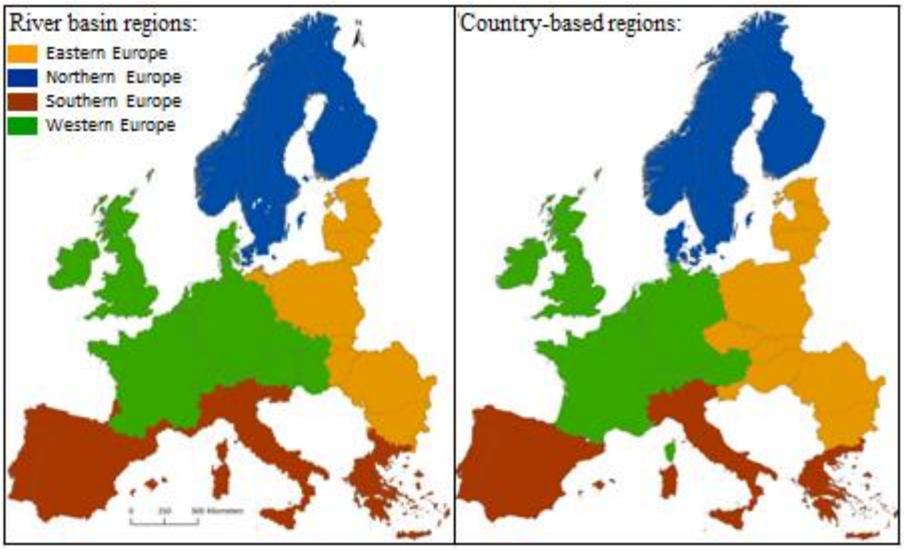


Figure 4.2: *Scale of analysis: river basin (left) and country-based (right) regional classifications of Europe*.

4.3 Sectors and Selected Impact Indicators

The CLIMSAVE IAP generates a large number of sectoral indicator variables, which were identified and prioritised based on the relevance for stakeholders and/or adaptation policy (Harrison *et al*. 2013; Holman and Harrison 2012). While these outputs provide a wide range of impact measuring indicators, this analysis focusses on seven key indicators (impact metrics) (Table 4.1). The indicators were selected based on inputs from sectoral experts after considering: (i) representativeness of the indicators for each sector/sub-system, (ii) reliability of the IAP in reproducing observed values of the indicators, and (iii) their relevance to stakeholders and decision-making on adaptation.

Table 4.1: *Descriptions of the selected impact indicators for each sector/sub-system*[17].

Sector/sub-system (Meta-model)	Impact Indicator, Abbreviation (Unit)	Indicator Description
Urban (RUG)	*Artificial*	The mean percentage change in artificial surfaces (i.e.,

[17] Note that the units of measurement for each indicator as shown here are used throughout the thesis (depending on the context within a particular section of the thesis' tables or figures or texts) in two ways, both in absolute terms, measured as: (i) values per the (10 x 10 arc-minutes) grid cells, and (ii) total (for FP, PF100, and TP)/average (for AS, BVI, WEI) aggregated by the five spatial extents considered (see Section 4.2). When this is not the case in other parts of the thesis, the indicators are presented as 'percentage change' relative to their respective baseline estimates, and this is clearly defined in the tables or figures or texts as appropriate.

	surfaces, AS (%)	CORINE land-cover class 1, representing residential and non-residential areas).
Flooding (CFFlood)	*People flooded in a 1 in 100 year event, PF100* (*millions*)	The number of people flooded by a 1 in 100 year (1%) event due to coastal and fluvial flooding.
Land use (SFARMOD + metaGOTILWA)	*Food production, FP* (*TJ*)	A measure of food productivity of land based on total food (or feed) produced as crops (wheat, maize, sunflower, potato, etc.) or livestock in terms of their metabolisable energy.
	Timber production, TP (*Mt*)	Total timber produced based on the modelled timber productivity of five representative species[18] within areas of modelled profitable managed forest.
	Land use diversity, LUD (–)	Representation of multi-functionality of the landscape based on Shannon Index (for land uses including urban, intensive arable, intensive grass, extensive grass, forest and others).
Water (WGMM)	*Water exploitation index, WEI* (–)	Dimensionless ratio of long-term annual water withdrawals to long-term annual renewable water resources. It is a water stress indicator based on the degree of pressure put on natural water resources by all water users.
Biodiversity (SPECIES)	*Biodiversity vulnerability index, BVI* (–)	An index based on changes in climate and habitat suitability for 12 representative species[19] covering a range of flora and fauna from different habitats and regions.

4.4 Sensitivity Analysis: One-Driver-At-a-Time (ODAT) Approach

Sensitivity analysis is the study of how the uncertainty or variation in model outputs can be (qualitatively/quantitatively) apportioned among the various model inputs (e.g., Saltelli *et al*. 2000). It is often identified as a critical pathway for improving knowledge, particularly when dealing with complex issues such as those surrounding uncertainties of climate change impacts and adaptation assessments (Kriegler *et al*. 2012). The CLIMSAVE IAP facilitates a comprehensive sensitivity analysis to investigate the response of indicators to changes in driver settings. This provides a better understanding of the relationships between input and output variables. Such assessment is necessary to understand outputs from complex IA methods such as scenario analysis (e.g., Harrison *et al*. 2015a) and uncertainty analysis (e.g., Brown *et al*. 2015). It allows the range of possible futures to be explored to identify how sectors/sub-systems respond to: (i) combined climate and socio-economic drivers and (ii) impacts that cross sectoral boundaries. The subsequent sub-sections present the range of climate and socio-economic drivers considered in the analysis and detailed description of implementation of the ODAT sensitivity analysis approach.

[18] The five representative European tree species considered are: (1) *Pinus sylvestris,* (2) *Pinus halepensis,* (3) *Pinus pinaster,* (4) *Quercus ilex,* & (5) *Fagus sylvatica*.

[19] The 12 selected mixed representative European species group are: (1) *Common poppy (Papaver rhoeas)*, (2) *Linnet (Carduelis cannabina)*, (3) *Bilberry (Vaccinium myrtillus)*, (4) *Hornbeam (Carpinus betulus)*, (5) *Norway spruce (Picea abies)*, (6) *Brown bear (Ursus arctos arctos)*, (7) *Western dappled white butterfly (Euchloe crameri)*, (8) *Common saltmarsh grass (Puccinellia maritima)*, (9) Strawberry clover (Trifolium fragiferum), (10) *Bell heather (Erica cinerea)*, (11) *Red deer (Cervus elaphas)*, & (12) *Capercaillie (Tetrao urogallus)*. The above list of species group is selected from the total of 111 species (included in the SPECIES model that has been trained and validated for all species) to represent a cross-section of species from different taxa, habitats, and regions in Europe.

4.4.1 Selected climate and socio-economic change drivers

CLIMSAVE considers two classes of underlying environmental change drivers, reflecting climatic and socio-economic change driving factors (Section 3.3). In this analysis, a range of these climatic and socio-economic drivers of change are explored in order to understand the relationships between drivers (represented by the IAP input driver variables) and sectoral responses (represented by the selected impact indicators, Table 4.1). Table 4.2 presents the full list of the 24 climatic and socio-economic input drivers (represented on the IAP user interface as *sliders*, i.e., continuous variables, and *buttons or dropdown menus*, i.e., discrete variables) and the ranges of values selected from each driver for this analysis.

While it is recognised that there are various definitions of drivers in the literature (e.g., Nelson *et al*. 2005), in this analysis the mechanisms by which a driver affects a given sectoral indicator are classified as: (a) *direct* if a driver affects a sector/sub-system as a direct IAP input to the meta-model from which the sectoral indicator was output, (b) *indirect* if a driver affects a sector/sub-system indirectly through its cascading effect on another sector/sub-system via the interconnected meta-model chain, and (c) *combined* if a driver affects a sector/sub-system both as a direct and indirect driver (e.g., Figure 4.3). For example, sea-level rise is a direct input variable into the flood meta-model that directly affects the number of people flooded. Conversely, food imports has an indirect impact on biodiversity through its impacts on land use patterns, which in turn affect habitat availability, thereby affecting the biodiversity vulnerability index. On the other hand, precipitation change has a combined effect on biodiversity, affecting the suitability of climate space for species (direct effect) as well as influencing the suitability of land use for different crop types, which in turn influence available habitat (indirect effect).

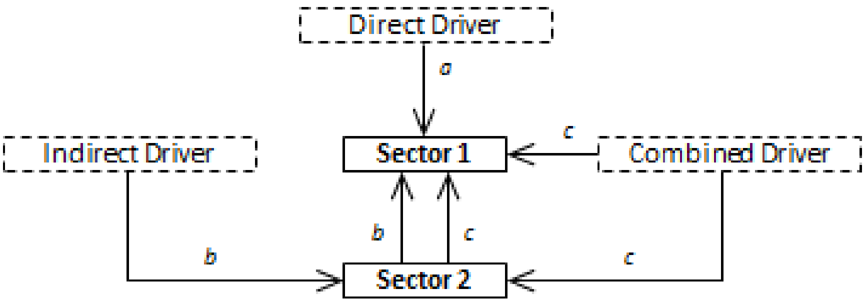


Figure 4.3: *Schematic diagram of sectoral interdependence and mechanisms by which a driver affects a sector/sub-system (in this case, Sector/Sub-system 1).*

Table 4.2: *List of the IAP climate and socio-economic change driver variables, their short names and associated input values selected for the ODAT sensitivity analysis.*

IAP DRIVER				Selected Sensitivity Values and Range			
Group/Sub-group		Input Variables (*Units*)	Short Name	Baseline	Minimum	Increment	Maximum
CLIMATE CHANGE DRIVERS:							
Climate:	1	*Annual temperature change (°C)*	Temp	0	0	1	6
	2	*Winter precipitation change (%)*	WPrec	0	-50	20	50
	3	*Summer precipitation change (%)*	SPrec	0	-50	20	50
	4	*CO_2 concentration (ppm)*	CO_2	350	350	50	700
	5	*Sea level change (m)*	SLR	0	0	0.25	2
SOCIO-ECONOMIC CHANGE DRIVERS:							
Social:	6	*Population change (%)*	Population	0	-50	20	50
	7	*Water savings due to behavioural change (%)*	StructChange	0	-50	20	50
	8	*Change in dietary preference for beef and lamb (%)*	Ruminant	0	-60	40	100
	9	*Change in dietary preference for chicken and pork (%)*	NonRuminant	0	-100	40	100
	10	*Household externalities preference (#)*	GreenRed	3	1	1	5
Economic:	11	*GDP change (%)*	GDP	0	-20	20	200
	12	*Change in oil price (%)*	OilPrice	0	0	80	400
	13	*Change in bioenergy production (%)*	BioEnergy	0	0	5	20
	14	*Change in food imports (%)*	ImportFactor	0	-20	20	60
Environmental:	15	*Set-aside (%)*	SetAside	3	0	2	8
	16	*Reducing diffuse source of pollution from irrigation (-)*	ReduceDiffuse	1	0.5	0.3	2
	17	*Forest management (-)*	ForestMgmt	Optimum		Options[a]	
Technological:	18	*Change in agricultural mechanisation (%)*	TechFactor	0	0	20	100
	19	*Water savings due to technological change (%)*	TechChange	0	-75	25	75
	20	*Change in agricultural yields (%)*	YieldFactor	0	-50	25	100
	21	*Change in irrigation efficiency (%)*	IrrigEfficiency	0	-50	25	100
Policy governance:	22	*Compact vs sprawled development (-)*	DevCompaction	Medium		Options[b]	
	23	*Attractiveness of coast (-)*	CoastAttract	Medium		Options[b]	
	24	*Water demand prioritization (-)*	WaterDistriRule	Baseline		Options[c]	
	25	*Level of flood protection (-)*	FloodProtection	Minimum		Options[d]	

Options:
[a] *Forest management* : [1] Optimum, [2] Un-evenaged, [3] Even-aged
[b] *Compact vs sprawled development /Attractiveness of coast* : [1] Low, [2] Medium, [3] High
[c] *Water demand prioritization* : [1] Baseline, [2] Prioritizing food production, [3] Prioritizing environmental needs, [4] Prioritizing domestic/industrial needs
[d] *Level of flood protection* : [1] No protection, [2] Minimum, [3] Maximum

See Table 3.1 for detailed descriptions of the variables. NB: Two variables (Coastal & Fluvial flood events) are excluded here as the thesis focuses only on a '100-year flood event'.

4.4.2 Application of the ODAT approach

In this analysis, the "*One-Driver-at-a-Time*" (ODAT) approach is used to assess the sensitivities of key European sectors/sub-systems to cross-sectoral impacts of both climatic and non-climatic drivers. The ODAT approach is a '*single-factor*' analysis where one input driver variable is modified, while keeping all remaining inputs at their baseline-default settings. Such an approach provides better understanding of the relationship between the input and output driver variables within the IAP. This will help to identify the key drivers that can be used to assess the effects of possible combinations (considering change in multiple drivers) of the key drivers. The results of this analysis will also be used for the next parts of the thesis: the more systematic and sophisticated sensitivity analysis using the MDAT scenario and uncertainty analysis approach followed by robustness assessment of adaptation policies (RAAP) (Figure 4.1). Figure 4.4 below presents descriptions of the key steps of the ODAT sensitivity analysis.

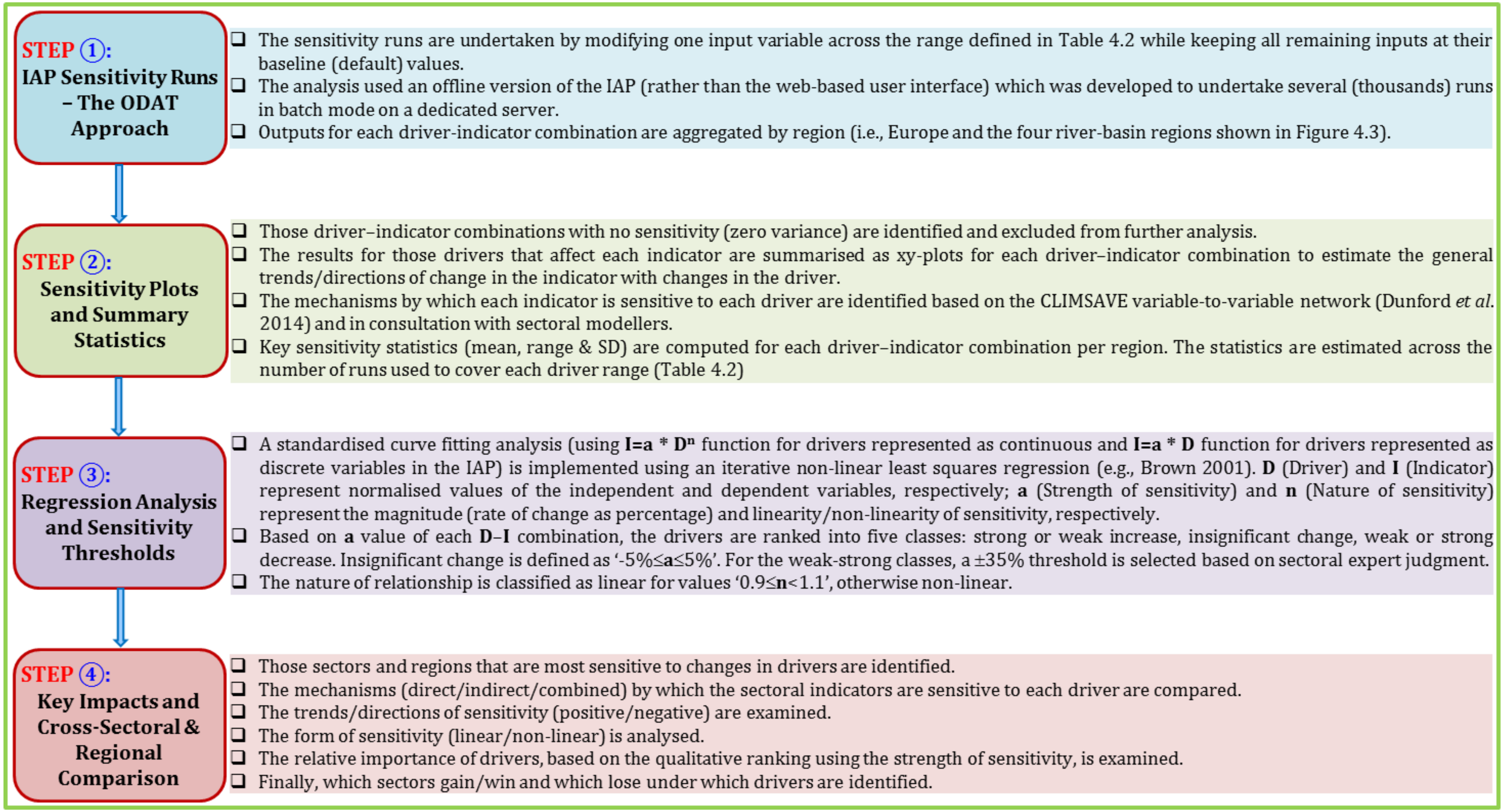


Figure 4.4: *Schematic methodological flowchart of the ODAT sensitivity analysis.*

Hence, building on the ODAT sensitivity analysis approach which is also used as a screening of the key climatic and socio-economic drivers, the next part of the research has focussed on:

(1) A comprehensive MDAT scenario and uncertainty analysis of the potential cross-sectoral impacts of a wide range of key climatic and socio-economic factors and scenario combinations to better understand the key sensitivities and uncertainties across the sectors/sub-systems, regions, and scenarios (Section 4.5), and

(2) Robustness assessment of a wide range of adaptation policy options to identify robust adaptation policies in Europe based on a comparison of the potential and residual cross-sectoral impacts under a range of selected scenarios that represent the uncertainty ranges (Section 4.6).

4.5 Scenario and Uncertainty Analysis: Multiple-Drivers-At-a-Time (MDAT) Approach

Policy and decision makers are faced with important challenges in terms of understanding the potential cross-sectoral impacts and long-term planning of future adaptation as well as mitigation policies. The problem is even more complicated, as the long-term social, economic, technological and political changes will take place on a spatial and temporal scale that is even more difficult to predict. Scenario analysis (also termed as future scenario planning) has been increasingly adopted by policy and decision makers as an important tool for assessing potential future impacts of and vulnerabilities to climate change and associated adaptation needs across a range of plausible futures (Alcamo 2001). Scenarios represent plausible narratives of alternative future worlds that describe future changes in drivers (problem explorations) and implications of alternative intervention policy options (solution exploration) (IPCC 2014). However, the common practice in a scenario analysis to date has been focussed more on understanding the effect of individual drivers of change that are rigidly combined within a given future scenario. While uncertainties of the predictions of these future climatic and socio-economic scenarios are accounted by considering an uncertainty range for individual drivers of change, the potential implications of the possible combinations of the various drivers within their individual uncertainty range is often limited to few scenario combinations of limited number of drivers at a time. This could potentially under-estimate (which could lead to unexpected consequences) and over-estimate (leading to more cost/investment than necessary/benefits) future adaptation needs. This is mainly, among others, due to two important issues: (1) lack of flexibility of assessment models to explore a wide range of scenario combinations which takes into account uncertainties of individual drivers and associated response of the system, and (2) limitations in computational power and runtime, especially within the team developing such assessment tools, as well as end users. Further, despite their capabilities, these issues are demonstrated in the lack of IAMs, either with appropriate flexibility to account the combined effects of climate change and socio-economic drivers, or limited applications of those which have some level of flexibility but never been applied comprehensively at regional scales (such as Europe) in order to inform adaptation policy-making.

4.5.1 Selected climate and socio-economic change drivers and scenarios

Figure 4.5 presents a schematic illustration of the key steps of the MDAT scenario and uncertainty analysis methodology. The analysis considers a wide ranging combinations (thousands scenario realisations) of the key climatic and socio-economic drivers identified following the ODAT analysis (see Section 5.4). The MDAT analysis explores the complex FWLE nexus interactions and associated future cross-sectoral impacts under the various scenarios (Chapter 6). The four key steps of the MDAT analysis outlined in Figure 4.5 are: (i) Identifying key driver combinations based on screening of the drivers following the ODAT analysis, (ii) Defining the scenario space and classes based on the driver combinations identified in (i), (iii) Evaluate the FWLE nexus under the scenarios, and (iv) Identify key sensitivities and uncertainties across the sectors/sub-systems, regions, and scenarios. Detailed descriptions of these steps are presented in Section 4.5.2. The approach focusses on two types of analysis: (i) a sensitivity analysis based on changes in multiple climatic and socio-economic drivers under the 'full ranges' of the MDAT scenarios investigated (see Figure 4.5), and (ii) uncertainty analysis and ensemble-based projections of the cross-sectoral impacts under a set of 'not-implausible' sample scenarios selected from the 'full ranges' of the MDAT scenarios. Building on the sensitivity analysis, the uncertainty analysis aims to provide plausible future projections of the potential cross-sectoral impacts based on the selected sample climate and socio-economic scenario ranges by excluding those scenarios that are considered 'implausible'. The implausibility analysis used to select the plausible set of scenarios is based on the approach presented in Edwards *et al*. (2011) (see Section 4.5.3 for more details).

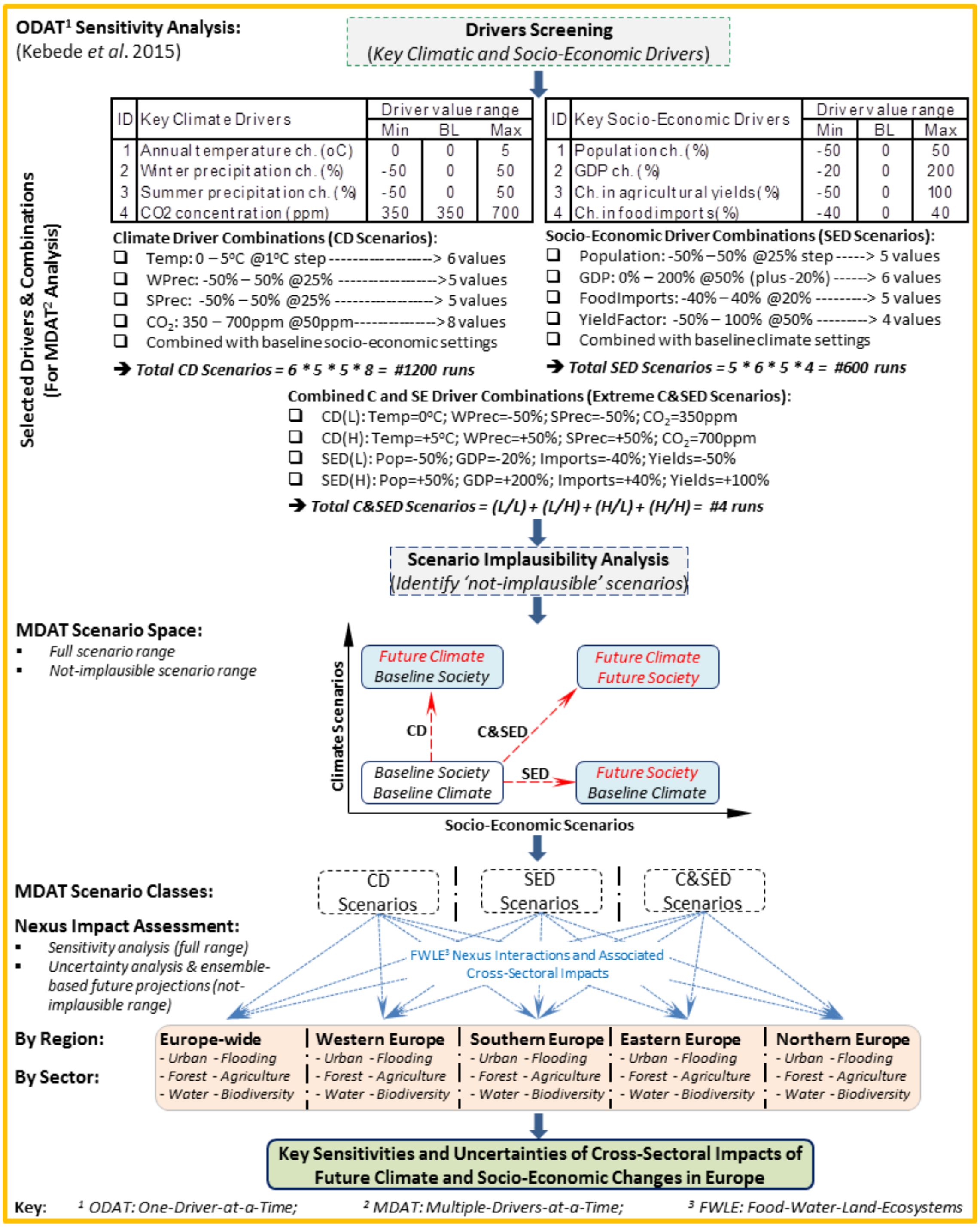


Figure 4.5: *Schematic methodological flowchart of the MDAT scenario and uncertainty analysis.*

4.5.2 Application of the MDAT approach

The MDAT scenario and uncertainty analysis follows a sophisticated sensitivity analysis based on a representative sample of the scenario space, which takes into account a wide range (thousands) of scenario combinations of the key drivers identified following the ODAT sensitivity analysis. The analysis provides a better understanding of the uncertainty of future impacts across the FWLE nexus sectors/sub-systems, regions, and scenarios considered. Such knowledge provides the best possible basis for effective decision-making on cross-sectoral adaptation planning. The method comprises four main steps (Figure 4.5) as discussed below:

Step 1: Identify the key climatic and socio-economic drivers considered in the MDAT analysis. Following the ODAT sensitivity analysis, the key drivers are selected based on a screening criterion of drivers with 'strong' and 'non-linear' effects on more than one sector/sub-system at the European scale to identify the most important climatic and socio-economic drivers considered in the MDAT analysis. Eight drivers have been identified (see Tables 5.3 and 5.4), including: Four climatic: (i) temperature, (ii) summer precipitation, (iii) winter precipitation, and (iv) CO_2 concentration; and Four socio-economic drivers: (i) population, (ii) GDP, (iii) food imports, and (iv) agricultural yields.

Step 2: Define MDAT's future scenario space and classes. The analysis considers three classes of scenarios representing: (i) Climate drivers only (CD), (ii) Socio-economic drivers only (SED), and (iii) Combined climate and socio-economic drivers (C&SED). The three scenario classes (CD, SED, and C&SED) allow exploring future changing scenario conditions considering the climate and socio-economic factors independently and combined. van Vuuren *et al*. (2014) illustrated that a wide range of socio-economic futures can produce similar climate changes. For example, certain projected hydrological changes can occur under a wide range of future demographic, social, economic and ecological conditions. Similarly the same future socio-economic conditions can be associated with a range of different climate futures. Hence, treating the climate and socio-economic scenarios both independently and combined will allow a comparison to identify the relative importance of these drivers and a better understanding of the complex interactions of the associated impacts across the sectors/sub-systems, regions, and scenarios. As highlighted in Section 4.5.1, the MDAT scenario and uncertainty analysis draws from two types of analysis: (i) a sensitivity analysis based on changes in multiple drivers considering the 'full range' of the MDAT scenarios investigated (Figure 4.5), and (ii) uncertainty analysis and ensemble simulations of future projections of the cross-sectoral impact based on plausible scenario samples selected from the full range MDAT scenario space (Section 4.5.3).

Step 3: Run the CLIMSAVE IAP at a batch mode for the defined scenario combinations of the key input drivers and evaluate the 'potential impacts' (i.e., without adaptation) across the sectors/sub-systems, region, and the various scenarios.

Step 4: Analyse the results for key sensitivities and uncertainties based on selected statistical metrics and indicators such as: the statistical significance of impacts from baseline, examining the spatial distribution of impacts, identifying the most sensitive sectors/sub-systems and regions and the relative importance of the key drivers and impacts, overall uncertainties of impacts across the sectors/sub-systems, regions, and scenarios.

The analyses results will then also be used for selecting the key scenarios that are used in the next stage of the research, i.e., robustness assessment of different adaptation policy options, based on selected clusters of adaptation strategies and estimating the 'residual impacts' (i.e., with adaptation) across the sectors/sub-systems, regions, and scenarios. The analysis identifies robust adaptation policies by evaluating the synergies, trade-offs and conflicts between the various adaptation policy options. This is discussed in Section 4.6.

4.5.3 Scenario implausibility analysis

As outlined in Figure 4.5, the MDAT analysis is based on a comparison of estimates of the key sensitivities and uncertainties of future cross-sectoral impacts of climate and socio-economic changes in Europe considering sensitivity analysis and ensemble simulations for future projections under a wide range of future scenarios. This is achieved by taking into account: (i) the 'full ranges' of the MDAT scenarios investigated (i.e., 1199 climate change scenarios and 599 socio-economic change scenarios), and (ii) a set of 'not-implausible' sample scenarios that are selected from the above 'full ranges' of scenarios. Investigation of these scenarios provides 'credible' future projections of the uncertainties in cross-sectoral impacts due to uncertainties of future changes in the key climatic and socio-economic factors and scenario combinations.

This section presents the approach used to identify the set of 'not-implausible' scenarios investigated. The method used here is based on the 'implausibility analysis' approach developed and applied by Edwards *et al*. (2011) for precalibrating the intermediate complexity climate model, GENIE-1 (also known as C-GOLDSTEIN; Edwards and Marsh 2005). Edwards *et al*. (2011) applied a sequential design experiment in order to assess the parameter-space of the climate model and identify "low-dimensional regions that are implausible" (p.1473). The analysis is based on identifying the model's precalibration outputs and 'physical' ranges by determining what is classed as 'non-physical' for the GINIE-1 model. In this study, the possible ranges of the sectoral impact indicators that are considered 'plausible' are identified based on a review of future scenario projections in the literature. The ranges are then used in order to identify a set of the MDAT scenarios investigated that could be considered as 'not-implausible'.

It is important to recognise that the use of the scenario projections reviewed from various studies to identify the 'plausible' ranges has its own limitations. This is mainly associated with the highly-heterogeneous nature (e.g., in terms of the diversity in the metrics, baseline, scales, scenarios, etc. used) of the various studies reviewed to identify the possible ranges. However, it is worth stating that, in the absence of clearly defined 'physical' ranges for the seven diverse cross-sectoral impact indicators (output metrics) investigated in this thesis, it provides an important initial insight to capture diverse 'expert opinions' and associated considerations of different assumptions and methods (e.g., sector-based studies to provide a basis for understanding future projections of key uncertainties in cross-sectoral implications of future climate and socio-economic changes).

Figure 4.6 presents a summary of the 'plausible' ranges and their percentile distributions for the various sectoral impact indicators (output parameters) investigated in this study based on the review. The summary presented includes projections from various studies, including multiple scenario projections of a given study (particularly their minimum and maximum projections). The broad range of estimates summarised here also highlights the high uncertainties in future projections of the potential impacts of future changing conditions in Europe. For example, when considering the average (± standard deviation) projections across the various studies, the future changes are estimated between: 3.3±2.2% for AS, 24,3±29.1% for BVI, 5.8±18.7% for FP, -2.0±25.1% for LUD, 10.3±21.6 for PF100, 10.2±20.4% for TP and 38.2±56.1% for WEI. These ranges of future projections are used as likely extreme ranges in order to identify the set of 'not-implausible' sample scenarios selected from the 'full ranges' of MDAT scenarios investigated (see Figure 4.5) The numbers of plausible scenario ranges are identified by excluding the MDAT scenarios that lead to future projections outside these ranges (see Section 6.6). The results provide plausible and consistent (across sectors/sub-systems, regions and scenarios) future projections of climate and socio-economic change impacts in Europe (based on area-aggregate summaries and spatial distribution mapping).

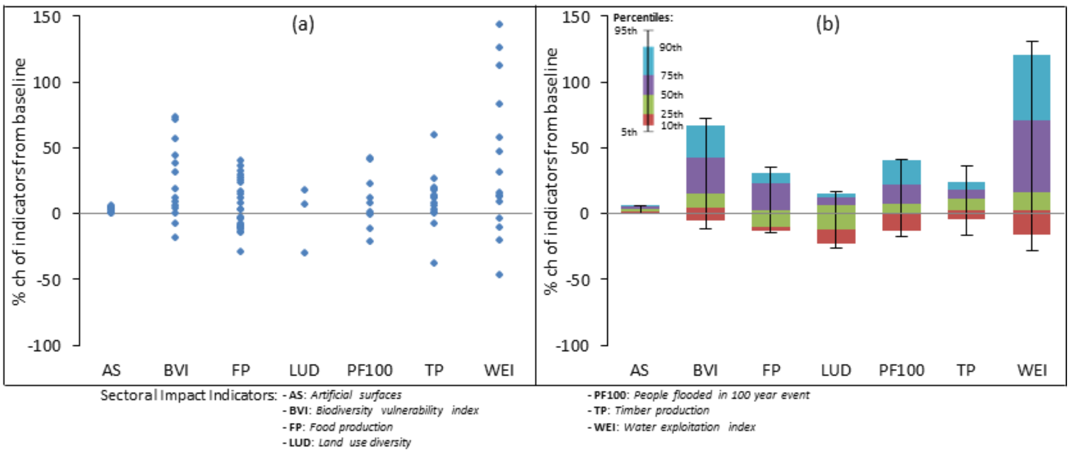


Figure 4.6: *Summary of the ranges (a) and percentile distributions (b) of future climate and socio-economic change impact projections in Europe based on a review of the literature (Appendix B).*

4.6 Robustness Assessment of Adaptation Policies

Robustness assessment is often considered as an important criterion for managing large decision uncertainty (Lempert *et al*. 2006). A robust adaptation strategy is defined here as one that has benefits in reducing impacts, i.e., performing well (compared with other alternatives) in reducing cross-sectoral impacts across the wide ranges of scenario futures (CD, SED, and C&SED scenarios), sectors/sub-systems (agriculture, biodiversity, flooding, forest, urban, and water), and regions (Europe and the four regions) considered (e.g., Table 4.4). Appropriate policy-options will help identify opportunities and list of different cross-sectoral adaptation strategies, which can assist decision-makers to develop policy-relevant roadmaps for future sustainable development and long-term adaptation planning. Following Jäger *et al*. (2015), the robustness assessment comprises three main steps:

Step 1: Identifying clusters of different adaptation strategies based on the list of sectoral adaptation options available within the CLIMSAVE IAP,

Step 2: Assessment of cross-sectoral impacts with adaptation (i.e., residual impacts) under each of the selected adaptation policy options, and

Step 3: Identifying robust adaptation policies based on a comparison of the 'potential' (without adaptation) and 'residual' impacts and associated synergies, conflicts and trade-offs to assess the benefits of adaptation in reducing impacts across the various sectors/sub-systems, regions and scenarios.

Each of these steps is further discussed in the following sub-sections.

4.6.1 Selected clusters of adaptation strategies

The selection of clusters of adaptation strategies aiming at testing the broader adaptation policy strategies in Europe considers the list of the sectoral adaptation options available within the CLIMSAVE IAP. The grouping of the adaptation options are based on defined narratives to achieve a certain purpose by each policy option (as discussed in Jäger *et al*. 2015). For the purpose of this study, four adaptation policy options are considered based on a particular focus on improving the different types of capitals under each adaptation policy option. The selected policy options are: (i) Behavioural adaptation – focussing on those adaptation measures that are aimed at reducing future impacts based on improving the human and social capitals (e.g., using education and awareness raising); (ii) Environmental adaptation – focussing on those adaptation measures that are aimed at reducing future impacts based on improving the natural capital (e.g., habitat creation and protecting the health of ecosystems);

(iii) Technological adaptation – focussing on those adaptation measures that are aimed at reducing future impacts based on improving the infrastructural capital (e.g., use of technology to improve irrigation, water use, flood defences, etc.); and (iv) A combined adaptation – this will consider a combination of all the above options focussing on improving all capitals, representing an ideal world[20]). Table 4.3 presents the list of adaptation strategies considered under each policy option.

Table 4.3: *List of adaptation strategy settings included under the four adaptation policy options considered in the robustness analysis.*

	CLIMSAVE IAP - ADAPTATION OPTIONS:	DEFAULT SETTINGS	ADAPTATION POLICY OPTIONS			
			Behavioural	Environmental	Technological	Combined
Social:						
1	Water savings due to behavioural change (%)	0	50%			50%
2	Change in dietary preference for beef and lamb (%)	0	-100%			-100%
3	Change in dietary preference for chicken and pork (%)	0	-100%			-100%
Economic:						
4	Change in bioenergy production (%)	0		20%		20%
5	Change in food imports (%)	0				40%
Technological:						
6	Improvement in agricultural mechanisation (%)	0			100%	100%
7	Water savings due to technological change (%)	0			75%	75%
8	Change in agricultural yields (%)	0			100%	100%
9	Improvement in irrigation efficiency (%)	0			100%	100%
Policy governance:						
10	Spatial planning for urban sprawl (Options)	Medium		High		High
11	Spatial planning for coastal development (Options)	Medium		High		High
12	Water demand prioritization (Options)	Baseline		Prioritizing environmental needs		Prioritizing food and env'tal needs
13	Flood risk management adaptation approach (Options)	No upgrade	Implement flood resilience (Yes)	Retreat of flood defences (Double)	Flood protection upgrade (1000%)	Implement a mixed response (Yes)
Environmental:						
14	Reducing diffuse source pollution from agriculture (-)	1		2	2	2
15	Forest Management - Tree species (Options)	Optimum	Un-evenaged		Optimum	Optimum
16	Protected area changed (%)	0		100%		100%
17	Change in protected area forest (%)	0		100%		100%
18	Method for allocating protected area (-)	Connectiv		Connectivity then Buffering		Connectivity then Buffering
Capitals:						
19	Human Capital	No change	H+			H+
20	Social Capital	No change	H+			H+
21	Manufactured Capital	No change			H+	H+

4.6.2 Assessment of cross-sectoral impacts before and after adaptation

The assessment of robustness of the selected adaptation policies uses a systematic evaluation matrix approach by identifying the adaptation option that most benefits in reducing impacts (i.e., identifying those options with minimum residual impacts) across all the scenarios, regions, and sectors/sub-systems. The analysis is based on a comparison of the potential (without adaptation) and residual (with adaptation) impacts, focussing on a selected set of scenarios of climate drivers only (CD), socio-economic drivers only (SED) and combined climate and socio-economic drivers (C&SED). The selected scenarios are those that represent the extreme uncertainty ranges of the cross-sectoral impacts at the European scale (i.e., the minimum and maximum percentage change in indicators from the baseline) for each impact indicator considered in the analysis. This is particularly useful in order to explore the overall uncertainties of the cross-sectoral residual impacts and associated benefits of the adaptation policy options across the different sectors/sub-systems, regions and scenarios. The measure of

[20] An idealistic scenario assuming that citizens, various stakeholders and policy-makers collectively act to live with nature sustainably through, for example, improved dietary preferences (e.g., reducing meat consumptions), efficient use of resources (e.g., food, water, land), creating space for the environment (e.g., increasing protected areas, maintaining wetland habitats, etc.), etc.

'residual' impacts provides a more realistic picture of future adaptation needs and opportunities than that of 'potential' impacts (PROVIA 2013a).

4.6.3 Identifying robust adaptation policies

An evaluation matrix is used to summarise the key trade-offs/conflicts and relative performance of the policy options by examining whether or not and by how much each policy option reduces impacts across the: (i) six sectors/sub-systems (agriculture, biodiversity, coasts, forest, urban, and water), (ii) five regions (Europe, western, southern, eastern, and northern), and (iii) various scenarios (including the climate drivers only (CD), socio-economic drivers only (SED), and combined climate and socio-economic drivers (C&SED)). Table 4.4 shows an illustrative evaluation matrix for assessing robustness of the various adaptation policy options across the sectors/sub-systems, regions, and scenarios.

Table 4.4: *An illustrative evaluation matrix for assessing robustness of the adaptation policy options.*

Sectors	Scenarios	Robustness Assessment of Adaptation Policies (RAAP)																				Robustness*
		Behavioural					Environmental					Technological					Combined					
		EU	WE	SE	EE	NE	EU	WE	SE	EE	NE	EU	WE	SE	EE	NE	EU	WE	SE	EE	NE	
Agriculture	CD	x				x			x					x					x			?
	SED			x																		
	C&SED							x														
Biodiversity	CD											x			x							?
	SED				x																	
	C&SED									x								x				
Coasts	CD					x																?
	SED																					
	C&SED											x			x					x		
Forest	CD	x		x			x															?
	SED									x												
	C&SED															x						
Urban	CD					x							x							x		?
	SED									x								x				
	C&SED			x												x						
Water	CD						x															?
	SED	x								x				x				x				
	C&SED																					
Robustness*		?					?					?					?					?

* Number of robustness criteria satisfied across the matrix.

5. RESULTS AND DISCUSSION (PART I): THE ONE-DRIVER-AT-A-TIME SENSITIVITY ANALYSIS

The ODAT sensitivity analysis results are summarised by focussing on the five key aspects of sensitivity of the different sectors/sub-systems and regions to cross-sectoral impacts in Europe under the various climatic and socio-economic change drivers considered (see Table 4.2):

(i) The sectoral interdependence that identifies the extent to which a sector/sub-system is sensitive to changes in other sectors/sub-systems,

(ii) The direction of influence of each driver that highlights whether an increase in the driver contributes to an increase or decrease in the sectoral indicator,

(iii) The nature of sensitivity which examines the linearity or non-linearity of the relationship for each driver–indicator combination,

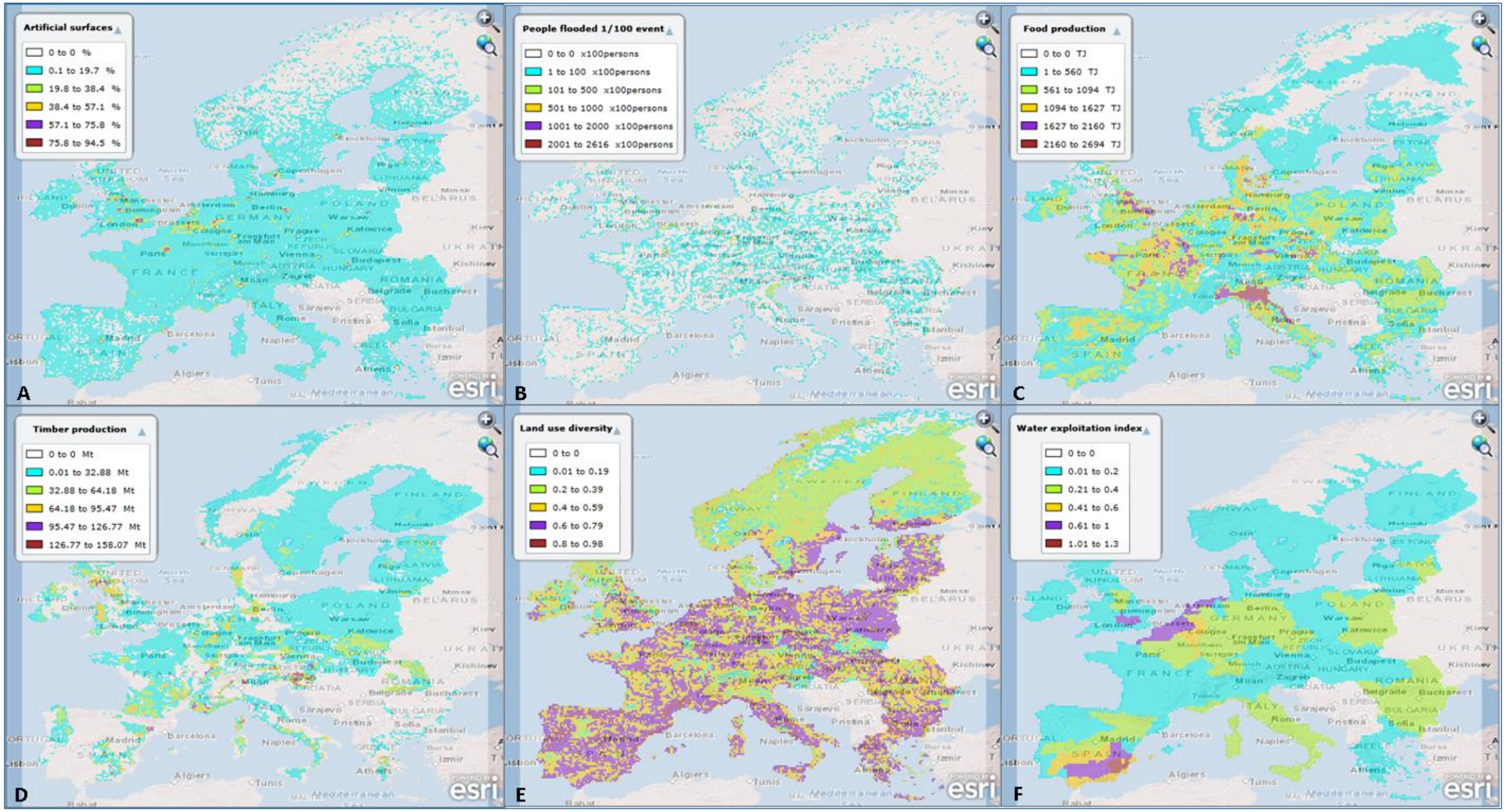
(iv) The level of contribution that each driver has on the sensitivity of each sectoral indicator, and

(v) The key drivers to which an indicator is sensitive.

These are discussed in the following sub-sections based on a Europe-wide and regional aggregated summary of the results, followed by comparisons of impacts across the sectors/sub-systems and regions.

5.1 European Sensitivity of Impacts and Sectoral Changes

Figure 5.1 shows baseline estimates of the sectoral indicators' spatial distribution at the European scale. For example, the distribution in AS shows the highest concentrations of residential/non-residential areas in western Europe, including the major cities with London representing the highest (94.5% AS coverage per grid cell). In terms of flooding, central and eastern European countries experience the highest flood (particularly fluvial) impacts associated with the low baseline standard of flood protection in the region. On the other hand, baseline water stress issues are concentrated in southern and western Europe. Table 5.1 presents a summary of the mechanisms of sensitivity and regional variations of the trends/directions of change (from baseline) of each sectoral indicator due to changes in the various climatic and socio-economic drivers. Table 5.2 then shows the Europe-wide sensitivity summary statistics (i.e., mean, range, and standard deviation). The results show significant differences between the sectors/sub-systems, as discussed below.



Key: (A) URBAN: *Artificial Surfaces, AS* (%)
(B) FLOODING: *People flooded by 100 year event, PF100* (x100 persons)
(C) AGRICULTURE: *Food production, FP* (TJ)
(D) FOREST: *Timber production, TP* (Mt)
(E) DIVERSITY: *Land use diversity, LUD* (–)
(F) WATER: *Water exploitation index, WEI* (–)

Note: *The BIODIVERSITY indicator (Biodiversity vulnerability index, BVI) is zero at the baseline.*

Figure 5.1: *Spatial distribution of the European estimates of the sectoral indicators at the baseline. Note: the values shown are per 10' x 10' grid cell.*

Table 5.1: *Summary of sensitivities of the sectoral indicators to changes in the climate and socio-economic drivers affecting each sector/sub-system.*

Drivers	SECTORS (Indicators)																																									
	Urban (AS)						Flooding (PF100)						Agriculture (FP)						Forest (TP)						Diversity (LUD)						Water (WEI)						Biodiversity (BVI)					
	Model Chain	EU	WE	SE	EE	NE	Model Chain	EU	WE	SE	EE	NE	Model Chain	EU	WE	SE	EE	NE	Model Chain	EU	WE	SE	EE	NE	Model Chain	EU	WE	SE	EE	NE	Model Chain	EU	WE	SE	EE	NE	Model Chain	EU	WE	SE	EE	NE
CLIMATE CHANGE DRIVERS:																																										
1 Temp	–	–	–	–	–	–	I[W]	↓	↓	↓	↓	↓	C[Fl,W]	↑	↑	↓	↑	↓	C[A]	↓	↓	↓	↓	↓	C[Fo]	↓	↑	↓	↑	↓	C[A]	↑	↑	↑	↑	↑	C[A]	↑	↑	↑	↑	↓
2 WPrec	–	–	–	–	–	–	I[W]	↑	↑	↑	↑	↑	C[Fl,W]	↙↘	↑	↓	↑	↙↘	C[A]	↑	↑	↙↘	↑	↑	C[Fo]	↙↘	↓	↑	↓	↑	C[A]	↓	↓	↓	↓	↓	C[A]	↓	↓	↓	↓	↓
3 SPrec	–	–	–	–	–	–	I[W]	↑	↑	↑	↑	↑	C[Fl,W]	↙↘	↙↘	↑	↙↘	↓	C[A]	↙↘	↙↘	↙↘	↑	↑	C[Fo]	↙↘	↙↘	↓	↙↘	↙↘	C[A]	↓	↓	↖↗	↓	↓	C[A]	↓	↓	↓	↓	↓
4 CO2	–	–	–	–	–	–	–	–	–	–	–	–	C[Fo]	↑	↑	↓	↓	↑	C[A]	↑	↓	↓	↑	↑	C[Fo]	↓	↓	↓	↓	↓	I[A,Fo]	↑	↑	↑	↑	↓	I[A,Fo]	↑	↑	↑	↑	↑
5 SLR	–	–	–	–	–	–	D	↑	↑	↑	↑	↑	I[Fl]	↓	↓	↓	↓	↓	I[A,Fl]	↓	↓	↓	↓	↓	I[Fl]	↓	↓	↓	↓	↓	I[A,Fl]	↓	↓	↓	↓	↓	I[A,Fl]	↑	↑	↑	↑	↑
SOCIO-ECONOMIC CHANGE DRIVERS:																																										
6 Population	D	↑	↑	↑	↑	↑	C[U]	↑	↑	↑	↑	↑	C[U,W]	↑	↑	↑	↑	↑	I[A,U]	↙↘	↙↘	↙↘	↙↘	↙↘	C[U]	↙↘	↙↘	↙↘	↙↘	↑	C[A]	↖↗	↑	↖↗	↖↗	↑	I[A]	↖↗	↖↗	↓	↖↗	↖↗
7 StructChange	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	D	↓	↓	↓	↓	↓	–	–	–	–	–	–
8 Ruminant	–	–	–	–	–	–	–	–	–	–	–	–	D	↑	↑	↑	↑	↑	I[A]	↙↘	↙↘	↙↘	↓	↙↘	D	↑	↑	↙↘	↖↗	↑	I[A]	↖↗	↓	↖↗	↖↗	↙↘	I[A]	↖↗	↖↗	↓	↖↗	↖↗
9 NonRuminant	–	–	–	–	–	–	–	–	–	–	–	–	D	↑	↑	↑	↑	↑	I[A]	↙↘	↙↘	↙↘	↓	↙↘	D	↙↘	↓	↙↘	↙↘	↑	I[A]	↖↗	↖↗	↖↗	↖↗	↓	I[A]	↓	↖↗	↓	↓	↓
10 GreenRed	D	↑	↑	↑	↑	↑	–	–	–	–	–	–	I[U]	↓	↓	↓	↓	↑	I[A,U]	↓	↓	↓	↓	↓	I[U]	↑	↑	↑	↑	↑	I[A,U]	↓	↓	↓	↓	↓	–	–	–	–	–	–
11 GDP	D	↑	↑	↑	↑	↑	–	–	–	–	–	–	C[U,W]	↙↘	↙↘	↑	↓	↑	I[A,U]	↙↘	↙↘	↙↘	↙↘	↙↘	C[U]	↙↘	↑	↖↗	↓	↙↘	C[A]	↖↗	↑	↖↗	↑	↖↗	I[A,U]	↖↗	↖↗	↑	↑	↓
12 OilPrice	–	–	–	–	–	–	–	–	–	–	–	–	D	↑	↑	↑	↓	↓	I[A]	↓	↓	↓	↓	↑	D	↓	↑	↑	↓	↓	I[A]	↑	↑	↑	↑	↓	I[A]	↑	↑	↓	↓	↑
13 BioEnergy	–	–	–	–	–	–	–	–	–	–	–	–	D	↑	↑	↑	↑	↑	I[A]	↓	↓	↓	↓	↓	D	↓	↓	↓	↑	↑	I[A]	↑	↑	↑	↑	↑	I[A]	↓	↑	↓	↓	↓
14 ImportFactor	–	–	–	–	–	–	–	–	–	–	–	–	D	↓	↓	↓	↓	↓	I[A]	↑	↑	↑	↑	↑	D	↙↘	↙↘	↙↘	↙↘	↓	I[A]	↓	↓	↓	↓	↓	I[A]	↖↗	↖↗	↑	↖↗	↖↗
15 SetAside	–	–	–	–	–	–	–	–	–	–	–	–	D	↓	↓	↓	↓	↑	I[A]	↓	↓	↓	↓	↓	D	↑	↓	↓	↑	↑	I[A]	↑	↓	↑	↓	↓	I[A]	↓	↑	↓	↓	↓
16 ReduceDiffuse	–	–	–	–	–	–	–	–	–	–	–	–	D	↑	↑	↙↘	↖↗	↑	I[A]	↙↘	↙↘	↙↘	↙↘	↙↘	D	↓	↙↘	↙↘	↙↘	↖↗	I[A]	↖↗	↑	↖↗	↖↗	↑	I[A]	↓	↖↗	↙↘	↓	↓
17 ForestMgmt	–	–	–	–	–	–	–	–	–	–	–	–	I[Fo]	↑	↑	↑	↑	↑	D	↓	↓	↓	↓	↓	I[Fo]	↑	↑	↑	↑	↓	I[A,Fo]	↑	↑	↑	↑	↑	I[A,Fo]	↑	↑	↑	↑	↑
18 TechFactor	–	–	–	–	–	–	–	–	–	–	–	–	D	↑	↓	↓	↑	↓	I[A]	↓	↓	↓	↓	↓	D	↓	↓	↓	↓	↑	I[A]	↓	↓	↓	↑	↓	I[A]	↑	↑	↓	↑	↑
19 TechChange	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	D	↓	↓	↓	↓	↓	–	–	–	–	–	–
20 YieldFactor	–	–	–	–	–	–	–	–	–	–	–	–	D	↑	↙↘	↑	↙↘	↓	I[A]	↙↘	↙↘	↙↘	↙↘	↙↘	D	↙↘	↙↘	↙↘	↙↘	↓	I[A]	↖↗	↖↗	↖↗	↖↗	↓	I[A]	↖↗	↖↗	↑	↖↗	↖↗
21 IrrigEfficiency	–	–	–	–	–	–	–	–	–	–	–	–	D	↙↘	↓	↑	↙↘	↙↘	I[A]	↙↘	↙↘	↙↘	↙↘	↙↘	D	↖↗	↖↗	↙↘	↖↗	↖↗	I[A]	↑	↑	↑	↑	↑	I[A]	↖↗	↖↗	↓	↖↗	↖↗
22 DevCompaction	D	↓	↓	↓	↓	↓	–	–	–	–	–	–	I[U]	↑	↑	↑	↑	↑	I[A,U]	↑	↑	↑	↑	↑	I[U]	↓	↓	↓	↓	↓	I[A,U]	↑	↑	↑	↑	↑	–	–	–	–	–	–
23 CoastAttract	D	↑	↑	↑	↑	↑	–	–	–	–	–	–	I[U]	↓	↓	↓	↓	↓	I[A,U]	↓	↓	↓	↓	↓	I[U]	↑	↑	↑	↑	↑	I[A,U]	↓	↓	↓	↓	↓	–	–	–	–	–	–
24 WaterDistriRule	–	–	–	–	–	–	–	–	–	–	–	–	I[W]	↓	↑	↓	↑	↑	I[A,W]	↓	↓	↓	↓	↓	I[W]	↓	↓	↓	↓	↓	C[A]	↓	↓	↓	↓	↓	I[A,W]	↑	↑	↑	↑	↑
25 FloodProtection	–	–	–	–	–	–	D	↓	↓	↓	↓	↓	I[Fl]	↑	↑	↑	↑	↑	I[A,Fl]	↑	↑	↑	↑	↑	I[Fl]	↑	↑	↑	↑	↓	I[A,Fl]	↑	↑	↑	↑	↑	I[A,Fl]	↓	↓	↓	↓	↓
Total # of Drivers:	**5**						**6**						**23**						**23**						**23**						**25**						**20**					
Direct (D):	*5*						*2*						*10*						*1*						*10*						*2*						*0*					
Indirect (I):	*0*						*3*						*7*						*18*						*7*						*17*						*5*					
Combined (C):	*0*						*1*						*6*						*4*						*6*						*6*						*15*					

Key:

- **Sectoral Indicators**: **AS** – Artificial surfaces, **PF100** – People flooded in a 1 in 100 year event, **FP** – Food production, **TP** – Timber production, **LUD** – Land use diversity, **WEI** – Water exploitation index, and **BVI** – Biodiversity vulnerability index.
- **Study Regions**: **EU** – Europe, **WE** – Western Europe, **SE** – Southern Europe, **EE** – Eastern Europe, and **NW** – Northern Europe.
- **Model Chain**: Mechanism of Sensitivity (**D**: Direct, **I**: Indirect, **C**: Combined) and Sector Initials: [**U**] Urban, [**Fl**] Flooding, [**A**] Agriculture, [**Fo**] Forest, [**W**] Water, and [**B**] Biodiversity.
- **Sensitivity Trends**: '**—**' Indictor is not sensitive to driver, **↑** Positive correlation (Indicator increases with increase in driver), **↓** Negative correlation (Indicator decrease with increase in driver), **↖↗** Minimum at baseline: Indicator increases with both increase and decrease in driver, and **↙↘** Maximum at baseline: Indicator decreases with both increase and decrease in driver.

Table 5.2: *A Europe-wide summary of the sensitivity of sectoral indicators to changes in various climate and socio-economic drivers.*

Drivers	SECTORS (Indicators)																				
	Urban (AS)			**Flooding (PF100)**			**Agriculture (FP)**			**Forest (TP)**			**Land use (LUD)**			**Water (WEI)**			**Biodiversity (BVI)**		
	BL = 3.67 %			*BL = 17.41 million*			*BL = 9843.5*1000TJ*			*BL = 262.28 Gt*			*BL = 0.8573*			*BL = 0.1452*			*BL = 0*		
	Mean	**Range**	**SD**	**Mean**	**Range**	**SD**	**Mean**	**Range**	**SD**	**Mean**	**Range**	**SD**	**Mean**	**Range**	**SD**	**Mean**	**Range**	**SD**	**Mean**	**Range**	**SD**
CLIMATE DRIVERS:																					
1 Temp	–	–	–	16.95	0.71	0.29	9933	305.6	103.4	158.3	159.0	58.0	0.806	0.074	0.030	0.192	0.081	0.027	0.110	0.268	0.097
2 WPrec	–	–	–	17.41	2.57	1.10	9891	276.8	106.6	229.9	160.9	64.7	0.842	0.080	0.031	0.172	0.203	0.076	0.007	0.155	0.057
3 SPrec	–	–	–	17.41	2.57	1.10	10014	519.7	193.0	176.3	257.8	109.6	0.796	0.125	0.049	0.174	0.144	0.057	0.026	0.304	0.111
4 CO_2	–	–	–	–	–	–	9792	345.2	110.1	278.1	32.8	8.9	0.776	0.145	0.052	0.142	0.012	0.004	0.043	0.090	0.031
5 SLR	–	–	–	26.82	17.21	5.94	9581	397.3	131.5	260.2	3.2	1.1	0.852	0.012	0.004	0.145	0.001	0.000	0.002	0.003	0.001
SOCIO-ECONOMIC DRIVERS:																					
6 Population	3.74	0.23	0.10	17.37	17.27	6.47	9894	10085	3831.0	147.4	248.7	92.4	0.761	0.856	0.093	0.160	0.024	0.009	0.053	0.163	0.059
7 StructChange	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	0.145	0.033	0.012	–	–	–
8 Ruminant	–	–	–	–	–	–	9934	760.6	272.4	237.7	76.4	34.7	0.849	0.105	0.042	0.149	0.006	0.003	0.006	0.010	0.005
9 NonRuminant	–	–	–	–	–	–	9558	5042.6	1714.5	245.7	95.3	38.5	0.830	0.079	0.036	0.150	0.011	0.005	0.010	0.042	0.017
10 GreenRed	3.69	0.03	0.01	–	–	–	9841	4.5	2.0	262.2	0.1	0.0	0.858	0.001	0.000	0.145	0.000	0.000	–	–	–
11 GDP	5.03	3.05	1.09	–	–	–	9819	612.6	185.3	236.4	45.6	12.9	0.840	0.034	0.014	0.200	0.101	0.036	0.010	0.016	0.005
12 OilPrice	–	–	–	–	–	–	10055	378.2	125.5	224.7	72.5	29.1	0.861	0.032	0.012	0.153	0.013	0.005	0.000	0.005	0.002
13 BioEnergy	–	–	–	–	–	–	9904	176.0	654.5	239.1	61.9	29.0	0.472	0.004	0.001	0.151	0.011	0.005	-0.003	0.005	0.002
14 ImportFactor	–	–	–	–	–	–	7413	9849.8	3897.3	236.9	131.8	58.6	0.748	0.286	0.121	0.146	0.021	0.008	0.060	0.165	0.069
15 SetAside	–	–	–	–	–	–	9550	567.2	243.7	263.7	30.1	13.5	0.472	0.002	0.001	0.145	0.002	0.002	-0.001	0.004	0.002
16 ReduceDiffuse	–	–	–	–	–	–	9888	720.9	286.7	202.7	101.0	43.6	0.850	0.003	0.001	0.156	0.012	0.005	0.001	0.015	0.005
17 ForestMgmt	–	–	–	–	–	–	9879	78.6	39.8	216.1	99.9	50.4	0.860	0.005	0.002	0.147	0.006	0.004	0.001	0.002	0.001
18 TechFactor	–	–	–	–	–	–	10061	469.7	164.2	231.8	47.8	16.4	0.835	0.045	0.017	0.147	0.004	0.002	0.006	0.013	0.005
19 TechChange	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	0.154	0.134	0.051	–	–	–
20 YieldFactor	–	–	–	–	–	–	9620	1956.2	688.1	197.3	262.3	107.1	0.779	0.135	0.048	0.184	0.142	0.048	0.046	0.083	0.031
21 IrrigEfficiency	–	–	–	–	–	–	9769	381.7	131.9	256.4	16.7	5.9	0.858	0.009	0.003	0.161	0.053	0.022	0.004	0.011	0.004
22 DevCompaction	3.68	0.04	0.02	–	–	–	9841	6.0	3.4	262.2	0.1	0.1	0.858	0.001	0.000	0.145	0.000	0.000	–	–	–
23 CoastAttract	3.67	0.01	0.00	–	–	–	9843	0.8	0.4	262.3	0.0	0.0	0.857	0.000	0.000	0.145	0.000	0.000	–	–	–
24 WaterDistriRule	–	–	–	–	–	–	9842	4.7	2.3	262.2	0.2	0.1	0.857	0.000	0.000	0.145	0.002	0.001	0.000	0.000	0.000
25 FloodProtection	–	–	–	15.49	27.58	13.89	9711	463.0	258.5	261.3	8.2	4.2	0.853	0.010	0.005	0.145	0.001	0.001	0.004	0.013	0.008

5.1.1 Urban: Artificial surfaces

Future urban growth (change in AS, in terms of residential and non-residential areas) is driven by five of the 20 socio-economic factors, while all the climatic drivers have no effect (Table 5.1). This is due to the urban model set-up (the variables included, Holman and Harrison 2012) and the fact that it is at the start of the meta-model chain (Figure 3.2), so the drivers can only have a direct effect. Change in AS shows the highest sensitivity to GDP growth, with a Europe-wide range greater than 3% (Table 5.2). It is followed by population growth with a Europe-wide range more than 0.2%, highlighting that these two variables are the two principal drivers of urban growth.

The sensitivity range for the three remaining socio-economic drivers (i.e., attractiveness of coast, development compaction and household externalities preference) is less than 0.05% (Table 5.2). However, it is worth noting that although these drivers have less effect on the amount of AS, they play an important role in determining the spatial distribution of changes in AS. These estimates are consistent with the RUG (Regional Urban Growth) meta-model structure (Holman and Harrison 2012). These changes (both in magnitude and spatial pattern) will have important indirect implications on other sectors/sub-systems as discussed below.

5.1.2 Flooding: People flooded in a 1 in 100 year flood event

Flooding (PF100) is sensitive to six (four climate and two socio-economic) of the 25 drivers (Table 5.1). The climate drivers (temperature and precipitation) have indirect effects (via the water sector/sub-system) on fluvial flooding through changes in river flood flows with a Europe-wide sensitivity range around 0.7 (temperature) and 2.6 (precipitation) million people (Table 5.2). Increasing temperature or decreasing precipitation results in a drier Europe (compared to the current climate) causing decreases in river flood flows, which lead to smaller fluvial floodplains, and hence fewer people affected. However, PF100 shows the highest sensitivity to changes in flood protection, sea level, and population; with a range greater than 17 million people. Flood protection has a direct effect on PF100, with higher defences reducing impacts significantly; it shows the highest sensitivity range of 27.6 million people (the Europe-wide total being reduced by a factor of about 40, from 28.3 million people under no protection to 0.7 million people under the maximum protection). This highlights the key importance of defences and more generally adaptation, which is also consistent with other studies, e.g., Hinkel *et al*. (2014) that demonstrated future flood impacts are more sensitive to applied protection strategies than climatic or socio-economic scenarios.

The direct effect of sea-level change is always negative; PF100 increases with sea-level rise due to the increase in areas at risk of coastal flooding. For example, under the extreme 2m sea-level rise, the Europe-wide total number of people flooded is estimated to double from the baseline estimate, reaching up to 35 million people. Conversely, the effect of population change is rather complex with a combined (direct/indirect) effect. It affects both coastal and fluvial flood impacts both through change in the number of people living within floodplains (i.e., more people in floodplains potentially means more people to be flooded) and via the change in urban growth (RUG model) influencing the distribution of AS (residential and non-residential areas) that affects where people live, including floodplains. These sensitivities and the illustrated CFFlood model behaviour help to interpret more complex changes simulated under multiple drivers (e.g., Mokrech *et al*. 2015; Chapter 6).

5.1.3 Land use indices: Food production, timber production and land use diversity

The land use indices, food production (FP), timber production (TP) and land use diversity (LUD) are all sensitive to 23 of the 25 drivers (Table 5.1). While 17 of these drivers have a Europe-wide sensitivity range greater than 275*1000TJ (for food) and 15Gt (for timber), 12 have a sensitivity range more than 0.03 units (for diversity) (Table 5.2). For FP, the top five drivers with the highest sensitivity range include changes in population, food imports, yield factor, and dietary (red and/or white meat) preferences. However, it is worth noting that as the land use allocation model (SFARMOD) uses an implicit in-built autonomous adaptation which prioritises food provision, the sensitivities to some of the drivers (e.g., that do not affect demand) is not fully picked up by the ODAT analysis as the model tries to maintain food production by re-allocating land use to meet the demand. However, this comes at the expense of other sectors/sub-systems that are affected by land use changes such as (managed) forestry and land use diversity. As a result, the sensitivity of forestry is rather complex as it is intimately connected with the distribution of intensive agriculture (see Audsley *et al*. 2015). As such, primary amongst the various drivers that have a large influence on all indicators (including TP and LUD) associated with land use change patterns are those factors that affect the distribution of intensive agriculture (and hence patterns of food production). Hence, TP is most sensitive to indirect socio-economic factors such as agricultural yields, population, and food imports, along with the climatic drivers (temperature and precipitations) with a sensitivity range greater than 130Gt (Table 5.2). For instance, an extreme decrease in crop yields results in areas which are currently forest becoming intensive agriculture to meet food provision demand, leading to a decline in TP. Similarly, an increasing population requires increased food production, which means that more land is used for agriculture leading to decline in areas for forest, and hence less TP. Moreover, the climatic factors that influence timber yields often also improve crop yields leading to complex interactions in terms of overall land profitability. Greater timber yield potential also leads to less forest area being needed to produce the same levels of timber, and as such allows losses in total forest area to more profitable land uses. Hence, temperature increase is found to reduce Europe-wide forest productivity, whilst increasing precipitation leads to increased (winter) and decreased (summer) productivity. Other important indirect drivers also include reducing diffuse source of pollution from irrigation, forest management approaches, and changes in oil price and dietary preferences (ruminant and non-ruminant) with a sensitivity range greater than 75Gt (Table 5.2).

Similarly, LUD is also driven by complex changes in different land uses including urban, intensive arable, intensive/extensive grassland, forest, and unmanaged. As diversity is greatest in areas (grid cells) where there is a broad mix of land use, LUD is positively influenced by drivers that lead to new land uses becoming present in a grid cell, provided that the changes are not at the expense of a total removal of another land use. Hence, the sensitivity of LUD is influenced positively by drivers that encourage agriculture to spread more widely into new areas (e.g., change in population and dietary preferences). Conversely, LUD is influenced negatively by factors that: make it easier to produce more food in less area (e.g., improvements in agricultural technology or crop yields); decrease the need for crop production (e.g., increase in food imports); make it harder for agriculture to spread (e.g., hotter and drier climates); and make other land uses more competitive (e.g., increases in CO_2 leading to increased timber yield).

5.1.4 Water: Water exploitation index

The water exploitation index (WEI) is sensitive to all of the 25 drivers, which directly and/or indirectly influence the amount of water use and/or availability (Table 5.1). Ten of these drivers have a Europe-wide sensitivity range greater than 0.02 units (Table 5.2). Those that affect the long-term annual water availability are precipitation and temperature. WEI shows the highest sensitivity to precipitation change: increasing precipitation leads to increasing water availability, thereby decreasing WEI (direct effect). Conversely, WEI increases with rising temperature due to decreasing water availability (direct effects); and on the water demand side, rising temperature lead to increasing irrigation water demand (indirect effects). In addition to the climatic factors, socio-economic drivers have a direct/indirect influence on water use by affecting water demand in the domestic, manufacturing and energy (cooling) sectors/sub-systems, as well as irrigation water withdrawals (driven mainly by the demand for crop production and change in prices for agricultural inputs). These include crop yields, water savings due to technological change, GDP growth, and irrigation efficiency with a sensitivity range greater than 0.05 units. The effect of changes in agricultural yields is always negative; both increasing and decreasing yields leading to increasing WEI. This is due to the fact that when yields increase the least productive agricultural areas become no longer profitable as the most productive areas are able to produce a greater proportion of the total food demand. This has the effect of increasing the marginal value of irrigation leading to higher WEI. Similarly, a decrease in yields means that more land is being used for agriculture (including in northern Europe) to meet existing food demand resulting in increasing irrigation water demand, thereby increasing WEI. GDP growth also leads to increasing WEI due to increasing income which (having unchanged population) increases domestic water use as more water-intensive appliances are used when people have higher incomes. Conversely, technological improvements have direct positive effect in reducing WEI through water savings due to increasing water efficiency in the domestic, manufacturing and energy sectors/sub-systems. Other drivers that also have some impact on WEI include: water savings due to behavioural change lowering domestic water use (↓WEI), population growth leading to higher domestic and irrigation (due to increased food demand) water use (↑WEI), and increasing food imports leading to declining irrigation water demand (↓WEI).

The sensitivities observed are consistent with the model structure which applies a water allocation scheme to derive actual water withdrawals in non-agricultural sectors/sub-systems as well as the maximum volume of water available for irrigation based on water availability and demand (Wimmer *et al*. 2015).

5.1.5 Biodiversity: Biodiversity vulnerability index

Out of the 25 drivers, 20 have some impact on the biodiversity index (BVI) (Table 5.1). Of these, eight have a Europe-wide impact with a sensitivity range greater than 0.02 units (Table 5.2). The BVI shows the highest sensitivity to climatic drivers. This is particularly true for summer precipitation and temperature. The influence of temperature is always negative; increasing temperature leading to increasing BVI due to decreases in the climate suitability for species, except in the NE region where a warmer climate become suitable for species from further south leading to an increase in the number of species present. However, changes in precipitation have an inverse relationship with BVI, where an increasing precipitation leads to a reduction in species' vulnerability whilst a decrease leads to increased vulnerability (Table 5.1). Also, changes at very low levels of precipitation show more pronounced effects than those at very high levels, i.e., changes from drought to dry conditions are more beneficial for most of the species than wet conditions becoming very wet. In addition to these climatic drivers, socio-economic factors that influence the distribution of land use are also shown to have indirect impacts on BVI. These include food imports, population growth, agricultural yields, and dietary preferences. Spatial analysis of the impacts of these factors reveal that land use changes often include the full removal of arable farming from grid cells which removes habitat for arable-related species such as the *Linnet* (*Carduelis cannabina*). Under some drivers such as agricultural yields, vulnerability increases with both increases and decreases in the driver. Increases in agricultural yields leads to productive agricultural areas producing more and those with lower productivity become less profitable and are prioritised for other uses, e.g., Southern Sweden losing its arable croplands. Conversely, when agricultural yields decrease farming in northern Europe increases to meet demand, but declines in areas such as Lithuania where the profitability of arable land is not as great.

This combined climate and socio-economic influence on BVI is expected and reflects the SPECIES bio-climatic envelope model that underpins the index (Holman and Harrison 2012). Climate determines the boundary conditions for the species and land use determines whether or not habitats are available within the climatically suitable areas. BVI is therefore sensitive to factors that influence either of these factors.

5.2 Regional Sensitivity of Impacts and Sectoral Changes

The sensitivities of impacts and sectoral changes show significant variations across the four European river-basin regions. This is discussed below focussing on the top 3–5 main drivers with the highest sensitivity range. The complete statistical summaries of the regional sensitivity are presented in Appendix B (Tables B0.1 (A–D)).

5.2.1 Urban: Artificial surfaces

As in the case for the Europe-wide sensitivity, the regional future urban growth is also driven by 5 of the 20 socio-economic drivers (no climate driver) (Table 5.1), but shows significant variation across the four regions (Tables B0.1 A–D). At the baseline, the largest distribution of AS is concentrated in western Europe, representing about 6.5% of artificial surfaces (residential/non-residential areas). Figure 5.2 shows the three main drivers (with high sensitivity range) for each region. Growth in GDP remains the dominant driver for future increase in AS in all regions, followed by population change, especially for western Europe. The highest sensitivity is also estimated in western Europe with a range about 6.4% (Table B0.1 (D) and Figure 5.2), which is also greater than the Europe-wide average (Table 5.2). For example, a 200% increase in GDP leads to doubling of AS in the region from 6.5% (at the baseline) to almost 13%. This is followed by southern Europe with a range about 2.8% (i.e., up from 3% AS at baseline) and northern Europe with a sensitivity range about 1.4% (i.e., up from 1.2% AS at baseline). Other drivers have relatively very small effect, they rather play an important role in terms of the spatial distribution of AS within each region.

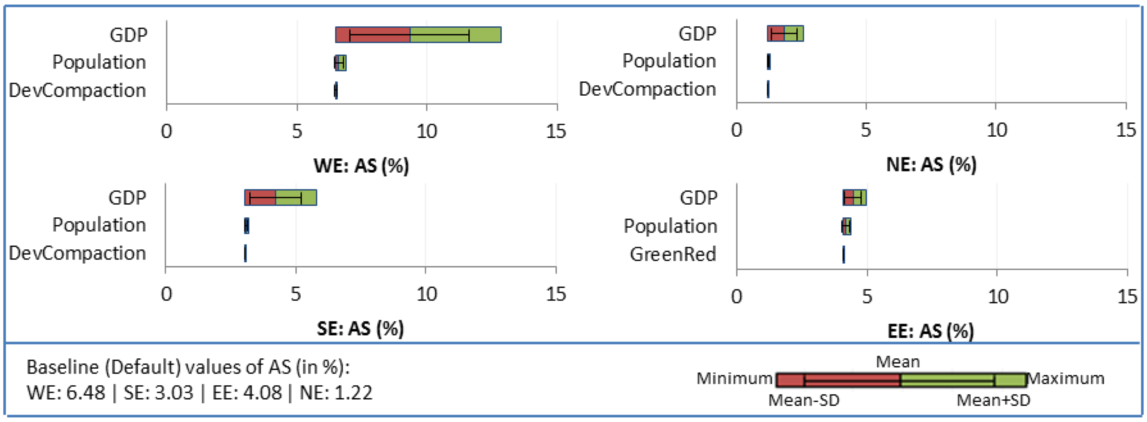


Figure 5.2: *Regional summary of the sensitivities of the average percentage area of artificial surfaces (AS) to changes in the top three drivers with the highest sensitivity range*.

5.2.2 Flooding: People flooded in a 1 in 100 year flood event

The regional impacts of flooding (PF100) are also sensitive to six (two climatic and four socio-economic) of the 25 drivers (Table 5.1), although with significant variations across the four regions. Figure 5.3 shows the three main drivers (with the highest sensitivity range) – with an increase in the drivers leading to increase in PF100, except for flood protection which has the opposite effect (Table 5.1). The highest sensitivity of PF100 occurs in western Europe, followed by eastern and southern Europe. For western Europe, while sea-level rise (with a sensitivity range of 14 million people) followed by population change (with 8.5 million people) are the major driving factors on PF100, the benefit of flood protection is also demonstrated by the significant reduction (from the baseline) of PF100 with the increase in standard of protection (with a sensitivity range greater than 18 million people: reducing from 19 million under no protection to 0.4 million people under maximum flood protection). In eastern Europe, population change is the main driver (with increase in PF100), followed by flood protection (decrease in PF100). The sensitivity of PF100 in northern Europe is relatively smaller than other regions (with sensitivity range less than 1.2 million people), mainly due to the relatively less population within floodplains in the region.

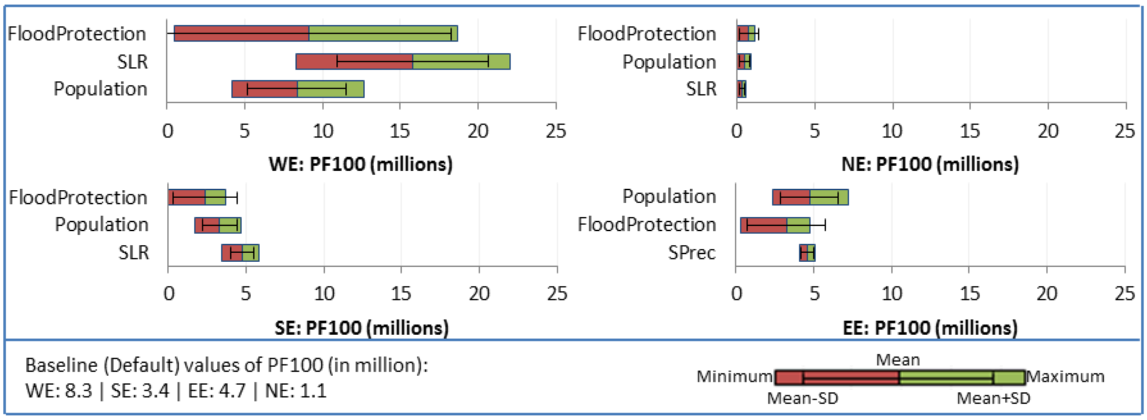


Figure 5.3: *Regional summary of the sensitivities of the total number of people flooded by a 1 in 100 year event (PF100) to changes in the top three drivers with the highest sensitivity range*.

5.2.3 Land use Indices: Food production, timber production and land use diversity

All the regional scale land use indices (i.e., FP, TP and LUD) are also sensitive to 23 of the 25 climatic and socio-economic drivers (see Table 5.1), but show important variations across the four European regions. Figure 5.4 presents the five main drivers of change in FP with a sensitivity range greater than 380*1000TJ (due to temperature change) across the four regions. Of the total of seven different drivers that are ranked in the top five in at least one of the regions, four of them have significant implications across all the four regions. These drivers are food imports, population and dietary preference (for largely grain-fed meat). In terms of the regional comparison, the highest sensitivity in FP is projected in western Europe with a range more than 4000*1000TJ due to changes in food imports and population; followed by eastern Europe, with a sensitivity range greater than 2000*1000TJ. In comparison, the least overall sensitivity is observed in northern Europe, with the highest range estimated at 1555*1000TJ due to population change.

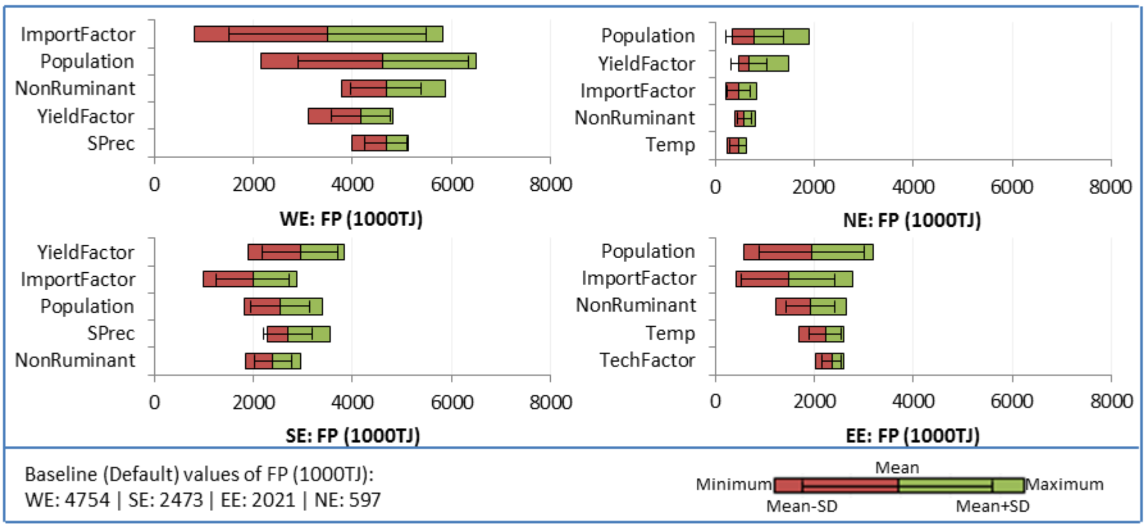


Figure 5.4: *Regional summary of the sensitivities of food production (FP) to changes in the top five drivers with the highest sensitivity range*.

Figure 5.5 shows the five main drivers (with highest sensitivity range) of change in TP with a sensitivity range greater than 28.5Gt (due to temperature change) across the regions. The highest sensitivity of TP occurs in western and northern Europe (with a range greater than 108Gt and 106Gt, respectively, due to change in summer precipitation), followed by eastern and southern Europe (with a range greater than 70Gt due to changes in summer precipitation and 36Gt due to changes in agricultural yields, respectively).

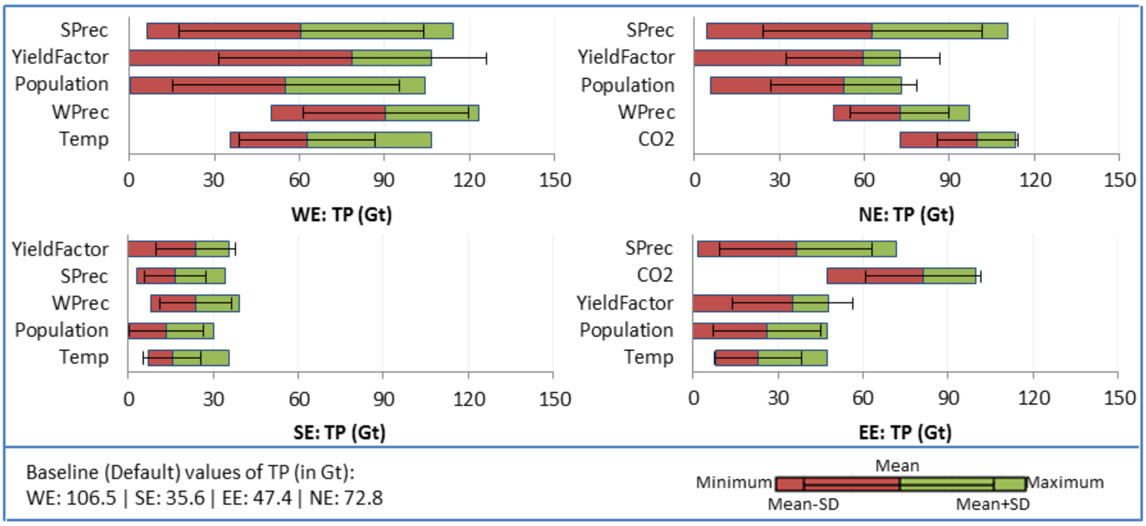


Figure 5.5: *Regional summary of the sensitivities of timber production (TP) to changes in the top five drivers with the highest sensitivity range*.

Similarly, Figure 5.6 shows the five main drivers of change in LUD with the highest sensitivity range varying from 0.12 units (due to CO_2 in western Europe) to 0.38 units (due to population change in eastern Europe). Of these, food imports, population, agricultural yields and temperature are the three major drivers of change in land use diversity across all regions.

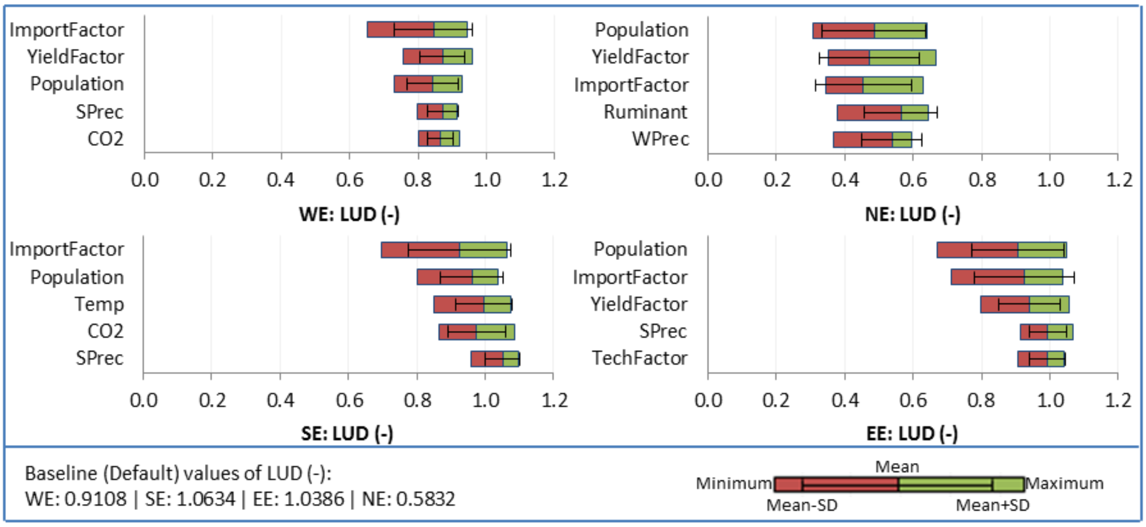


Figure 5.6: *Regional summary of the sensitivities of land use diversity (LUD) to changes in the top five drivers with the highest sensitivity range*.

5.2.4 Water: Water exploitation index

The regional water exploitation index (WEI) is also sensitive to all of the 25 climatic and socio-economic drivers (Table 5.1), but shows significant variations across the four regions. Figure 5.7 shows the top five (with highest sensitivity range) drivers affecting WEI in each region. The highest sensitivity is observed in southern Europe, with a sensitivity range under the five key drivers estimated between 0.2 – 0.5 units. Winter precipitation and GDP changes (combined drivers) and agricultural yields (indirect driver due to irrigation water use) are the three major drivers in southern Europe; followed by eastern Europe with a sensitivity range 0.2 – 0.3 units under the five key drivers. The sensitivity of WEI in northern Europe is relatively very small under all drivers (< 0.005 units), mainly due to the relatively higher supply (availability) and less demand of water in the region.

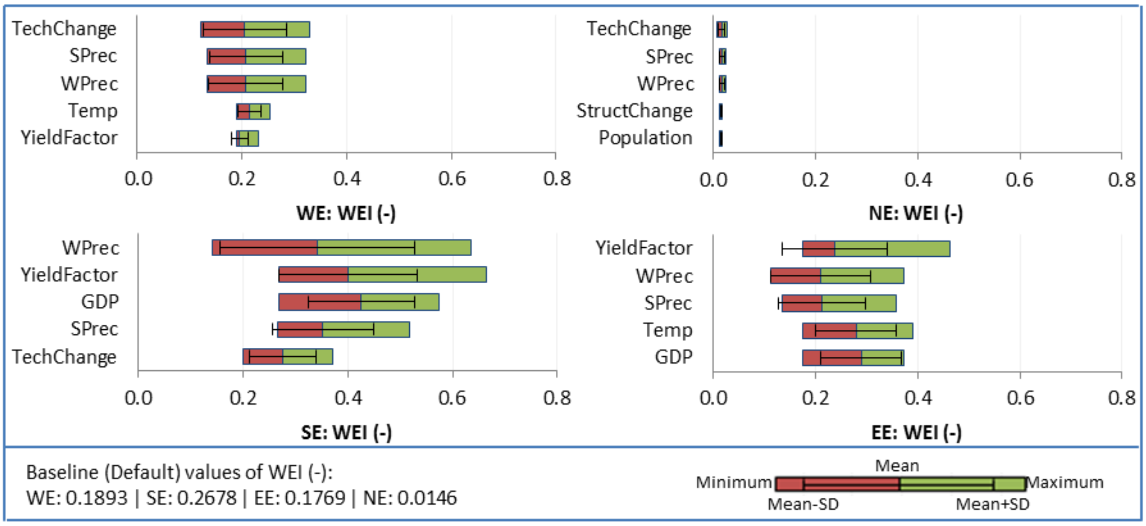


Figure 5.7: *Regional summary of the sensitivities of water exploitation index (WEI) to change in the top five drivers with the highest sensitivity range*.

5.2.5 Biodiversity: Biodiversity vulnerability index

As in the Europe-wide case, the regional biodiversity vulnerability index (BVI) is also sensitive to 20 out of the 25 climatic and socio-economic drivers (Table 5.1), but shows significant variations across the four regions. Figure 5.8 presents a summary of the top five drivers (with highest sensitivity range) affecting BVI in each region. The results show that the climate drivers (temperature and precipitation) have important implications in all regions: increase in temperature leading to increase in BVI (except in northern Europe, which rather benefit due to the northward movement of some species from the south), while increase in precipitation leading to decrease in BVI in all regions, although variable in magnitude. The highest sensitivity of BVI is observed in southern Europe, with a sensitivity range under the five key drivers estimated between 0.2 units (indirect effect of population change) and 0.6 units (combined effect of temperature change). This is followed by eastern and western Europe and then the northern Europe, with sensitivity ranges under the five drivers varying between 0.13 – 0.42 units (eastern), 0.13 – 0.47 units (western), and 0.07 – 0.32 units (northern).

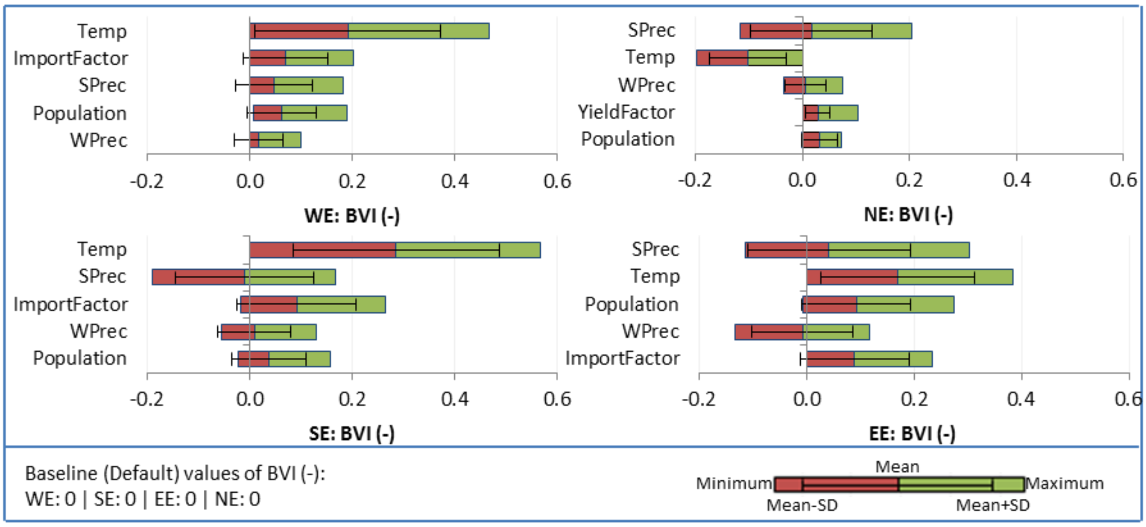


Figure 5.8: *Regional summary of the sensitivities of biodiversity vulnerability index (BVI) to changes in the top five drivers with the highest sensitivity range*.

5.3 Nature of Sensitivity and Ranking of Drivers: Cross-Sectoral & Regional Comparison

The standardised regression analysis is used to identifying the form of sensitivity (linearity/non-linearity) and the relative importance (five-class qualitative ranking) of the wide ranges of climatic and socio-economic drivers affecting each sectoral indicator. This analysis allowed a cross-sectoral and cross-regional comparison of impacts and identification of which sectors/sub-systems lose and which gain/win and under which key drivers. Table 5.3 summarises the nature/form of sensitivities representing the linearity/non-linearity of each driver-indicator combination at the European scale. The results show that at the European level, 19 out of the 25 drivers have a non-linear effect on one or more of the sectors/sub-systems (representing about 70% of the total driver-indicator combinations). Most of the non-linearities observed are related to drivers that have some indirect effects on the sectoral indicators. The urban sector/sub-system is the exception, as all its drivers are direct. About 30% (38 out of 125) of the driver-indicator relationships are direct (excluding direct effects of the combined drivers). Almost 79% of these (30 out of the total 38 direct driver-indicator combinations) also appears to have non-linear effects on all sectors/sub-systems, except biodiversity. In contrast, the indirect/combined drivers represent 57 of the 87 non-linear driver-indicator combinations. These results highlight the complexity and highly non-linear nature of the cross-sectoral interactions due to the cascading indirect impacts of most of the climatic and socio-economic change drivers across the sectors/sub-systems and regions. This further highlights the fact that ignoring or having a limited understanding of these interactions could lead to potential under- or over-estimation of impacts, including the possible non-linear amplifications of such interactions on the impacts (e.g., Ludwig *et al*. 2013), with potential implications on estimates of future adaptation needs.

Table 5.3: *A Europe-wide summary of the form of sensitivity (linearity/non-linearity) of each driver–indicator combination*.

Drivers		Sectoral Indicators							Summary	
		AS	PF100	FP	TP	LUD	WEI	BVI		
CLIMATE DRIVERS:										
1	Temp	–	NL	NL	NL	NL	NL	NL		
2	WPrec	–	NL	NL	NL	NL	NL	NL		
3	SPrec	–	NL	NL	NL	NL	NL	NL		
4	CO_2	–	–	NL	NL	NL	NL	L		
5	SLR	–	NL	NL	NL	L	NL	L		
SOCIO-ECONOMIC DRIVERS:										
6	Population	NL	L	L	NL	NL	NL	NL		
7	StructChange	–	–	–	–	–	L	–		
8	Ruminant	–	–	NL	NL	NL	NL	NL		
9	NonRuminant	–	–	NL	NL	NL	NL	NL		
10	GreenRed	NL	–	NL	NL	NL	NL	–		
11	GDP	NL	–	NL	NL	NL	NL	NL		
12	OilPrice	–	–	NL	L	L	NL	NL		
13	BioEnergy	–	–	L	NL	NL	L	NL		
14	ImportFactor	–	–	NL	NL	NL	NL	NL		
15	SetAside	–	–	NL	NL	NL	NL	NL		
16	ReduceDiffuse	–	–	NL	NL	NL	NL	NL		
17	ForestMgmt	–	–	L	L	L	L	L		
18	TechFactor	–	–	NL	NL	L	NL	L		
19	TechChange	–	–	–	–	–	NL	–		
20	YieldFactor	–	–	NL	NL	NL	NL	NL		
21	IrrigEfficiency	–	–	NL	NL	NL	NL	NL		
22	DevCompaction	L	–	L	L	L	L	–		
23	CoastAttract	L	–	L	L	L	L	–		
24	WaterDistriRule	–	–	L	L	L	L	L		
25	FloodProtection	–	L	L	L	L	L	L		
TOTAL: # of Drivers		**5**	**6**	**23**	**23**	**23**	**25**	**20**	**125**	
Linear:	**Direct**	*2*	*1*	*1*	*1*	*2*	*1*	*0*	*8*	**38**
	Indirect	*0*	*0*	*5*	*5*	*6*	*5*	*6*	*27*	
	Combined	*0*	*1*	*1*	*0*	*0*	*1*	*0*	*3*	
Non-linear:	**Direct**	*3*	*1*	*9*	*8*	*8*	*1*	*0*	*30*	**87**
	Indirect	*0*	*3*	*2*	*4*	*1*	*12*	*11*	*33*	
	Combined	*0*	*0*	*5*	*5*	*6*	*5*	*3*	*24*	

Indicators:
AS: Artificial surfaces
PF100: People flooded in a 1 in 100 year event
FP: Food production
TP: Timber production
LUD: Land use diversity
WEI: Water exploitation index
BVI: Biodiversity vulnerability index

Table 5.4 presents a summary of the 5-class qualitative ranking of the drivers based on the strength/magnitude of sensitivity for each driver-indicator combination. The results highlight the varied level of contribution of each driver to the overall sensitivity of each sectoral indicator across the regions. It also illustrates the sectoral winners (reduced impacts) and losers (increased impacts) as discussed below.

Table 5.4: *A 5-class ranking of the drivers based on the strength/magnitude of sensitivity of cross-sectoral impacts for each driver-indicator combination.*

Drivers	SECTORS (Indicators)																																		
	Urban (AS)					Flooding (PF100)					Agriculture (FP)					Forest (TP)					Land use (LUD)					Water (WEI)					Biodiversity (BVI)				
	EU	WE	SE	EE	NE	EU	WE	SE	EE	NE	EU	WE	SE	EE	NE	EU	WE	SE	EE	NE	EU	WE	SE	EE	NE	EU	WE	SE	EE	NE	EU	WE	SE	EE	NE
CLIMATE DRIVERS:																																			
1 Temp	–	–	–	–	–	I/-	I/-	I/-	I/-	I/-	I/+	WI	WD	WI	SD	SD	SD	WD	WD	WD	WD	WI	WD	WI	WD	SI	WI	I/+	WI	I/+	SI	SI	SI	SI	WD
2 WPrec	–	–	–	–	–	WI	WI	I/+	WI	I/+	I/-	I/+	WD	WI	I/-	SI	SI	WD	WI	SI	I/-	WD	WI	I/-	WI	SD	WD	SD	SD	I/-	SD	WD	WD	WD	WD
3 SPrec	–	–	–	–	–	WI	WI	I/+	WI	I/+	I/-	WD	WI	WD	I/-	SD	SD	WD	SI	SI	SD	SD	WD	WD	WD	SD	WD	SI	SD	I/-	SD	WD	SD	SD	SD
4 CO2	–	–	–	–	–	–	–	–	–	–	I/+	WI	SD	WD	I/+	SI	SD	WD	SI	SI	SD	SD	WD	WD	WD	I/+	I/+	WI	I/+	I/-	WI	WI	WI	WI	I/+
5 SLR	–	–	–	–	–	SI	SI	WI	I/+	I/+	I/-	I/-	I/-	I/-	I/-	I/-	I/-	I/-	I/-	I/-	I/-	I/-	I/-	I/-	I/-	I/-	I/-	I/-	I/-	I/-	I/+	I/+	I/+	I/+	I/+
SOCIO-ECONOMIC DRIVERS:																																			
6 Population	WI	I/+	I/+	I/+	I/+	SI	SI	WI	WI	I/+	SI	SI	WI	SI	WI	SD	SD	WD	WD	SD	SD	SD	WD	SD	WI	WI	I/+	WI	I/+	I/+	SI	WI	WD	WI	WI
7 StructChange	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	WD	WD	WD	WD	I/-	–	–	–	–	–
8 Ruminant	–	–	–	–	–	–	–	–	–	–	WI	I/+	I/+	I/+	I/+	WD	WD	WD	WD	WD	WI	I/+	WD	WI	WI	I/+	I/-	WI	I/+	I/-	I/+	I/+	I/-	I/+	I/+
9 NonRuminant	–	–	–	–	–	–	–	–	–	–	WI	WI	WI	WI	WI	WD	SD	WD	WD	WD	WD	SD	WD	WD	WI	WI	I/+	WI	I/+	I/-	WD	I/+	WD	WD	I/-
10 GreenRed	I/+	I/+	I/+	I/+	I/+	–	–	–	–	–	I/-	I/-	I/-	I/-	I/+	I/-	I/-	I/-	I/-	I/-	I/+	I/+	I/+	I/+	I/+	I/-	I/-	I/-	I/-	I/-	–	–	–	–	–
11 GDP	SI	SI	WI	WI	WI	–	–	–	–	–	I/-	WD	WI	WD	SI	WD	WD	WD	I/-	WD	WD	WI	+	WI	WD	SI	I/+	SI	SI	I/+	WI	I/+	I/+	WI	I/-
12 OilPrice	–	–	–	–	–	–	–	–	–	–	I/-	WI	I/+	I/-	I/-	WD	WD	WD	WD	WI	WD	WI	WI	I/-	WD	WI	I/+	WI	I/+	I/-	I/+	I/+	I/-	I/-	I/+
13 BioEnergy	–	–	–	–	–	–	–	–	–	–	WI	WI	I/+	I/+	I/+	SD	WD	WD	I/-	I/-	I/-	WD	I/-	I/+	I/+	I/+	I/+	WI	I/+	I/+	I/-	I/+	I/-	I/-	I/-
14 ImportFactor	–	–	–	–	–	–	–	–	–	–	SD	SD	WD	SD	WD	SI	SI	WI	WI	WI	SD	WD	SD	SD	SD	WD	I/-	WD	I/-	I/-	SI	WI	WI	WI	I/+
15 SetAside	–	–	–	–	–	–	–	–	–	–	WD	WD	I/-	I/-	I/-	WD	WD	I/-	WD	I/-	I/+	I/-	I/-	I/+	I/-	I/+	I/-	I/+	I/-	I/-	I/-	I/+	I/-	I/-	I/-
16 ReduceDiffuse	–	–	–	–	–	–	–	–	–	–	WI	WI	I/-	WI	I/+	SD	SD	WD	WD	WD	I/-	WD	I/-	I/-	WI	WI	I/+	WI	I/+	I/+	I/-	I/+	I/-	I/-	I/-
17 ForestMgmt	–	–	–	–	–	–	–	–	–	–	I/+	I/+	I/+	I/+	I/+	WD	WD	WD	WD	WD	I/+	I/+	I/+	WI	WD	I/+	I/+	WI	I/+	I/+	I/+	I/+	I/+	I/+	I/+
18 TechFactor	–	–	–	–	–	–	–	–	–	–	I/+	I/-	I/-	WI	I/-	WD	WD	WD	WD	I/-	WD	WD	WD	WD	I/+	I/-	I/-	I/-	I/+	WD	I/+	I/+	I/-	I/+	I/+
19 TechChange	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	SD	WD	WD	WD	I/-	–	–	–	–	–
20 YieldFactor	–	–	–	–	–	–	–	–	–	–	WI	WD	WI	I/-	WD	SD	SD	SD	WD	SD	SD	WD	WD	WD	SD	WI	I/+	WI	WI	I/-	WI	WI	WI	WI	WI
21 IrrigEfficiency	–	–	–	–	–	–	–	–	–	–	I/-	WD	WI	I/-	I/-	WD	WD	WD	I/-	I/-	WI	WI	I/-	+	+	WI	I/+	WI	WI	I/+	I/+	I/+	I/-	I/+	I/+
22 DevCompaction	I/-	I/-	I/-	I/-	I/-	–	–	–	–	–	I/+	I/+	I/+	I/+	I/+	I/+	I/+	I/+	I/+	I/+	I/-	I/-	I/-	I/-	I/-	I/+	I/+	I/+	I/+	I/+	–	–	–	–	–
23 CoastAttract	I/+	I/+	I/+	I/+	I/+	–	–	–	–	–	I/-	I/-	I/-	I/-	I/-	I/-	I/-	I/-	I/-	I/-	I/+	I/+	I/+	I/+	I/+	I/-	I/-	I/-	I/-	I/-	–	–	–	–	–
24 WaterDistriRule	–	–	–	–	–	–	–	–	–	–	I/-	I/+	I/-	I/+	I/+	I/-	I/-	I/-	I/-	I/-	I/-	I/-	I/-	I/-	I/-	I/-	I/-	I/-	I/-	I/-	I/+	I/+	I/+	I/+	I/+
25 FloodProtection	–	–	–	–	–	SD	SD	WD	WD	WD	I/+	I/+	I/+	I/+	I/+	I/+	I/+	I/+	I/+	I/+	I/+	I/+	I/+	I/+	I/-	I/+	I/+	I/+	I/+	I/+	I/-	I/-	I/-	I/-	I/-
Summary:	5					6					23					23					23					25					20				
Strong	**1**	*1*	*0*	*0*	*0*	**3**	*3*	*0*	*0*	*0*	**2**	*2*	*1*	*2*	*2*	**9**	*9*	*1*	*2*	*5*	**5**	*4*	*1*	*1*	*2*	**5**	*0*	*3*	*3*	*0*	**5**	*1*	*2*	*2*	*1*
Weak	**1**	*0*	*1*	*1*	*1*	**2**	*2*	*3*	*4*	*1*	**6**	*11*	*9*	*8*	*4*	**8**	*8*	*15*	*11*	*8*	**7**	*10*	*10*	*10*	*11*	**8**	*5*	*13*	*5*	*1*	**4**	*6*	*6*	*7*	*4*
Insignificant	**3**	*4*	*4*	*4*	*4*	**1**	*1*	*3*	*2*	*5*	**15**	*10*	*13*	*13*	*17*	**6**	*6*	*7*	*10*	*10*	**11**	*9*	*12*	*12*	*10*	**12**	*20*	*9*	*17*	*24*	**11**	*13*	*12*	*11*	*15*

Ranking Classes:				
	SI	Strong Increase	SD	Strong Decrease
	WI	Weak Increase	WD	Weak Decrease
	I/+	Insignificant (Small increase)	I/-	Insignificant (Small decrease)
	–	Indicator is not sensitive to the drivers		

5.3.1 Cross-sectoral comparison of impacts at the European scale

At the European scale, 13 of the 25 climate and socio-economic drivers have strong (positive/negative) implications on one or more of the sectors/sub-systems (Table 5.4). As discussed in Section 5.1.3, for FP, while there are varied regional implications the effect of most drivers at the European scale is relatively weak/insignificant. The exception is for the two key drivers (population and food imports) that directly affect food demand, which leads to an increase in production to meet the increased demand. Due to the implicit assumption in food prioritization within the land use model, for other drivers which don't affect food demand (e.g., the climatic factors), the model maintains food production through land use re-allocation at the expense of other sectors/sub-systems (e.g., forestry). The relatively small sensitivities of FP to most drivers at the European scale reflect this. The combined effects of the various drivers with conflicting implications on both food demand and production are investigated in the MDAT analysis (discussed in Chapter 6).

In contrast, when looking at other sectors/sub-systems a warmer future climate generally has negative impacts on most sectors/sub-systems; biodiversity, water, and forest being the main losers followed by land use diversity. However, increases in precipitation are positive for biodiversity and water leading to strong decreases in biodiversity vulnerability and water stress. Conversely, land use diversity loses with higher summer precipitation. Flooding also increases significantly with sea-level rise. In contrast, forestry gains strongly with increasing CO_2, which has a knock-on effect on other sectors/sub-systems; increasing timber yield leading to productive areas producing more of the total timber and large areas becoming abandoned, negatively affecting biodiversity and land use diversity. The implications of climatic drivers on other sectors/sub-systems are relatively small.

When considering socio-economic drivers, while a wealthier future Europe (higher GDP) is expected to experience a strong urban growth, it will lead to significant stresses on water resources due to the associated additional pressures on water demand. The forest, land use diversity, and biodiversity sectors/sub-systems also lose with increasing GDP (albeit relatively weak in magnitude) via its influence on land use distribution such as associated increased labour costs leading to increased crop prices, thereby increasing irrigation profitability in some areas (e.g., the new EU countries). Similarly, increasing population has a negative effect on most sectors/sub-systems; the flooding, forest, land use diversity, and biodiversity sectors/sub-systems being the major losers, followed by the water sector/sub-system. Other key socio-economic drivers include change in agricultural yields, food imports and dietary preferences, which have varied indirect implications across all sectors/sub-systems. For example, increasing food imports reduces the need for agriculture, which has a knock-on effect on other sectors /sub-systems, with biodiversity and land use diversity being the major losers. Conversely, the forest and water sectors win in this situation due to more land being available for forestry and declining irrigation water demand reducing the stress on water. Flooding also reduces with increased flood protection.

5.3.2 Cross-sectoral comparison of impacts at the regional scale

Table 5.4 shows that 7 (southern and eastern) to 12 (western) of the 25 climate and socio-economic drivers have strong (positive/negative) regional implications on one or more of the sectors/sub-systems. A warmer climate has significant regional negative impact on the forest and biodiversity sectors/sub-systems; forest losing in all regions (particularly strongly in western), and biodiversity also losing significantly in all regions (except north). This is followed by the water and agriculture sectors/sub-systems, also water losing in western/eastern Europe due to declining water availability and increasing demand for irrigation and agriculture losing in northern and southern Europe due to a fall in yields for most crops. Higher temperatures also have varied regional effects on land use diversity; losing in southern/northern and gaining in western/eastern Europe (but with a weak magnitude). However, forestry gains strongly in eastern/northern with increasing CO_2, due to relatively higher profitability when compared with western/southern Europe. In contrast, biodiversity loses in all regions (except north) with higher CO_2. In terms of precipitation, the biodiversity and water sectors/sub-systems are the winners. For water, increasing (both summer and winter) precipitation leads to a strong decrease in WEI, particularly in southern/eastern followed by western Europe. For biodiversity, summer precipitation is found to be more important in terms of vulnerability than winter precipitation in all regions (except western). In contrast, forest shows significant regional variation with precipitation change, which most, if not all, of the time is due to associated indirect implications on agricultural land use change. For example, forest strongly gains with increasing winter precipitation, but strongly loses with increasing summer precipitation in western Europe. This is due to lower relative profitability in western than northern/eastern Europe, in particular, where increases in precipitation leads to increasing TP. Flooding also increases with increased precipitation, particularly in western/eastern Europe (although this trend is relatively weak in strength).

In terms of the socio-economic drivers, those identified with Europe-wide relevance also have important regional implications for each sector/sub-system (Table 5.4). These include population, GDP, agricultural yields, food imports and dietary preferences. In addition, forest management, reducing diffuse sources of pollution from irrigation and irrigation efficiency have notable implications. For example, forestry consistently loses in all regions with changes in agricultural yields due to the associated changes in the relative profitability of forestry and agricultural land use. Similarly, biodiversity (in all regions) and water (southern/eastern) also lose, again related to changes in irrigation water demand (stress on water) and changes in arable farming (effect on biodiversity). Conversely, increasing food imports has positive implications on forest (increasing TP in all regions, especially in western), water (especially in southern) and biodiversity (in all regions).

However, it is worth noting that these results do not account for non-linearities and impacts associated with changes in multiple drivers, as some scenario combinations could have much higher impacts than those presented here. This is investigated in the MDAT analysis (Chapter 6). Nonetheless, it provides important sectoral and cross-sectoral insights on the effects of individual drivers/stresses and helps identify the relative importance of drivers across sectors/sub-systems and regions. This provides a better understanding of the combined effects of different climate/non-climate drivers (e.g., as represented by scenarios of different driver combinations considered in the MDAT analysis) on each sector/sub-system and the associated complex cross-sectoral nexus interactions. Building on this analysis, Harrison *et al*. (2015a) also investigated the cross-sectoral implications of a selected range of climatic and socio-economic scenario futures, which accounts for a combination of multiple driver changes considered as part of the four CLIMSAVE socio-economic scenarios (Section 3.5.2). As such, these analyses provide important information to understand the potential benefits/conflicts of different adaptation measures across sectors/sub-systems (e.g., Berry *et al*., 2015).

5.4 Summary

This chapter presented the sensitivity analysis results based on the ODAT (One-Driver-at-a-Time) approach. The main focus of the analysis was to track if, and how, the direct effect of an individual (climatic or socio-economic) driver on a sector/sub-system or region is transferred and felt by other sectors/sub-systems or regions, in order to identify: (i) those sectors and regions most sensitive to future changes (i.e., which sector/sub-system or region gain or lose most under a given change of a driver), (ii) the mechanisms of sensitivity (i.e., whether the effect of the drivers on each sectoral indicator is ‘direct’ or ‘indirect’ or ‘combined’), (iii) the trends and directions of sensitivity in terms of the influence of each driver on the sensitivity of the indicators (i.e., whether an increase in the driver contributes to an increase or decrease in the indicators), (iv) the form or nature of sensitivity (i.e., in terms of ‘linearity’ or ‘non-linearity’ of the relationship for each driver-indicator combinations), (v) the magnitudes or strength of sensitivity (i.e., in terms of whether the relative rate of change of an indicator due the change in a driver is ‘strong’ or ‘weak’ or ‘insignificant’), and (vi) the relative importance of the key drivers across the sectors/sub-systems and regions. Such an analysis helps to better understand and interpret outputs from complex integrated assessments (as in the case of the CLIMSAVE IAP) of cross-sectoral impacts of climatic and socio-economic factors under changes in multiple drivers, as illustrated in Chapter 6.

The results highlight that a large number (20 out of 25) of the (climatic and socio-economic) drivers affect most sectors/sub-systems either directly or indirectly (see Table 5.1) with varying levels of magnitude across the sectors/sub-systems and regions (see Sections 5.1 and 5.2). At the European scale, eight drivers are identified as key parameters, with important cross-sectoral implications (i.e., ‘strong’ and ‘non-linear’ impacts on more than one sector) (as presented in Table 5.4). These include four climatic factors (i.e., changes in temperature, summer precipitation, winter precipitation, and CO_2 concentration) and four socio-economic factors (i.e., changes in population, GDP, food imports, and agricultural yields). These drivers are used in the MDAT (Multiple-Drivers-at-a-Time)-based scenario and uncertainty analysis (see Chapter 6) considering a wide range of scenario combinations between the eight key parameters, considering the ‘full’ and selected ‘not-implausible’ ranges of the MDAT scenarios (see Figure 4.5 and Sections 4.5.2 and 4.5.3 for more details on the scenario combinations considered).

6. RESULTS AND DISCUSSION (PART II): THE MULTIPLE-DRIVERS-AT-A-TIME SCENARIO AND UNCERTAINTY ANALYSIS

Scenario analysis has often been identified as a strategic management tool to explore future uncertainties and support robust decision making under changing climate and socio-economic conditions (e.g., Postma and Liebl 2005; Jones *et al*. 2014). Most climate change studies use a scenario approach to assess the potential impacts of and possible adaptation to climate and/or socio-economic changes by exploring a selected set of plausible alternative futures. However, it has been argued that future changes in socio-economic systems have been insufficiently integrated with an analysis of climate change impacts (e.g., Berkhout *et al*. 2002). It has also been highlighted that integrated assessments and participatory methods of scenario development are ideal approaches for analysing the potential implications of changes in socio-economic systems along with impacts associated with climate change. To this end, multiple-scenario analysis has been the forefront approach to estimate uncertainties surrounding future impacts of and hence adaptation needs to changes in climate as well as socio-economic factors (e.g., Postma and Liebl 2005). Most impact assessment studies to date consider a limited (usually four) number of scenarios with a particular focus on the uncertainties of individual (climate and/or socio-economic) drivers rather than considering the possible key combinations of these drivers, which can allow to systematically represent the overall spectrum of uncertainty of changes in the drivers and associated impacts. However, such analyses based on only a limited number of scenarios may not produce reliable results (PROVIA 2013a), as they may omit important scenario combinations which could potentially under- or over-estimate future adaptation needs. This highlights the need for a more comprehensive analysis based on a diverse and large set of plausible futures exploring a wide range of scenario combinations. Such approaches allow estimating the overall uncertainties of the potential cross-sectoral impacts and adaptation needs across the ranges of scenarios. Use of such multiple-scenario based analysis is in fact an advanced and more sophisticated sensitivity analysis in terms of exploring the overall uncertainty based on a comprehensive representation of the scenario space. This provides the additional advantage that a better understanding of the system is obtained (PROVIA 2013a).

This chapter presents the results of an extensive application of the CLIMSAVE IAP based on a systematic scenario and uncertainty analysis of cross-sectoral impacts under changes in multiple climatic and socio-economic drivers. The MDAT analysis considers thousands of scenario combinations of the eight key drivers identified in the ODAT analysis. It provides a better understanding of the key sensitivities and uncertainties of the FWLE nexus interactions and associated cross-sectoral impacts of future changes in climate as well as social, economic, technological, and policy governance in Europe. The analysis will also help identify the scenarios with extreme uncertainty ranges of future impacts, which are used to assess the cross-sectoral synergies, conflicts and trade-offs between wide ranges of adaptation strategies (Section 7.3.2).

The analysis focused on seven selected sectoral impact indicators (Table 4.1). The following sub-sections present the key results and discussions of the MDAT scenario and uncertainty analysis based on a comparison of impacts under: (1) the 'full', and (2) a selected 'not implausible' ranges of the MDAT climate and socio-economic scenarios considered (see Section 4.5). The results are summarised and presented for Europe and the four regions, focusing on: (i) statistical significance of the regional aggregated mean changes in indicators from their baseline estimate, (ii) sensitivities of the indicators under changes in the various key climatic and socio-economic drivers and scenario combinations, (iii) uncertainties of the cross-sectoral impacts due to uncertainties of the climate and socio-economic change scenarios, (iv) the spatial distribution of changes in indicators across the various scenarios, and (v) a summary of the key scenarios identified for assessing the potential cross-sectoral implications and robustness of the adaptation policy options in the RAAP analysis.

As discussed in Section 1.2, broadly there are two main sources of uncertainty associated with IA modelling studies, as in the case with the CLIMSAVE IAP, which are: scenario and model uncertainties. Dunford *et al*. (2014) developed and applied a mixed-method approach to address these uncertainties within the CLIMSAVE IAP based on "formal numerical approaches, modeller interviews and network analysis" (p.417). The analysis provides a holistic assessment of the scenario and model uncertainties in input data and model parameters in the meta-models' networked linkages integrated within the CLIMSAVE IAP. Building on the ODAT sensitivity analysis (Kebede *et al*. 2015) and the qualitative uncertainty analysis (Dunford *et al*. 2015) of the IAP, Brown *et al*. (2015) also provides a quantitative assessment of the form and extent of aggregate uncertainties of the IAP. Their results have shown that there is "*no evidence that the IAP misrepresents known relationships or exaggerates uncertainties about the processes it models*" (p.303). They also demonstrated the ability of the IAP to handle extreme inputs "*without compromising output reliability*" (p.303). However, they also highlighted the importance of future development of methods to reduce/quantify the remaining inaccuracies. The analysis also stressed the benefits of effective use of the IAP for "*illuminating the real-world processes that have been modelled*" (p.304); including in terms of improving understanding of the potential cross-sectoral impacts of and adaptation to future climate and socio-economic changes in Europe. Nonetheless, it is important to note that the results presented in this thesis should be considered within the broader contexts and key IAP uncertainties presented in Brown *et al*. (2015) and Dunford *et al*. (2015).

Therefore, the analysis results presented in this chapter focusses on sensitivities and uncertainties of future cross-sectoral impacts due to uncertainties associated with changes in the key climatic and socio-economic input parameters (identified based on the ODAT sensitivity analysis, Chapter 5), given the CLIMSAVE IAP model assumptions (including the use of meta-modelling approach in the IAP[21]). This is done by exploring the ranges of possible responses of the selected impact indicators associated with uncertainties of the input drivers and their scenario combinations (see Figure 4.5). While it is important to recognise that model uncertainties associated with the individual sector/sub-system models cannot be ruled out, this aspect is not discussed here. However, it is worth stating here that most of the meta-models (and/or the original models, which the meta-models are derived from) were subjected to rigorous testing and validations (e.g., Morales *et al*. 2005; Harrison *et al*. 2006; Audsley *et al*. 2015; Mokrech *et al*. 2015; Wimmer *et al*. 2015). Detailed descriptions of the key assumptions and the development and validation of the individual sectoral meta-models integrated within the IAP can be found in Holman and Harrison (2012). Nonetheless, it is important to note that the results presented in the subsequent sections of this chapter should be considered within the broader contexts and key IAP uncertainties outlined above (see Brown *et al*. 2015; Dunford *et al*. 2015) for more detail).

6.1 Statistical Significance of Cross-Sectoral Impacts at European and Regional Scales

A paired t-test analysis using a 5% significance threshold was conducted to determine and identify if there are statistically significant mean differences between baseline and future projections of the sectoral indicators under the various scenario combinations explored. The analysis was summarised under the three classes of scenarios: (1) climate drivers only (CD, with a total of 1199 model runs), (2) socio-economic drivers only (SED, with a total of 599 model runs), and (3) combined extreme climate and socio-economic scenarios (C&SED, with a total of 8 extreme model runs) (Section 4.5.1). The results are discussed in the following sub-sections. The groupings (as presented in Tables 6.1/6.2 and Figure 6.1 based on average

[21] It is worth noting that this "*__is necessary to enable modelling across the spatial and sectoral range covered and to allow the rapid simulation of a range of possible scenarios__*" (Brown *et al*. 2015; p.304), although meta-models have their limitations as in the case in most approaches used in IA exercises.

percentage of the number of pairs of a scenario-vs-baseline model runs within each scenario class) are made to provide aggregate comparison across the various regions, indicators, and scenario groups. However, it is worth noting that the tests are performed (i.e., for all the 23,871 10x10-arcminutes grid cells and aggregated for the five spatial extents investigated) based on an independent comparison of each scenario against the baseline estimate for each indicator, i.e., considering each of the various scenarios developed within the three scenario classes (i.e., CD, SED, C&SED) individually against the baseline.

6.1.1 Due to climate change scenarios

Table 6.1 presents a summary of the statistical significance analysis (based on a 5% significance threshold) of the changes in indicators from baseline estimates for Europe and the four regions under the various climate scenarios.

Table 6.1: *European and regional average % of the number of indicator-scenario combinations that are statistically significantly different from baseline across the climate scenarios.*

	Indicators	Climate scenarios grouped by CO_2 emission level (ppm)								All scenarios	All sectors & scenarios
		350	400	450	500	550	600	650	700		
EU	BVI	99.3	98.0	96.0	99.3	98.0	98.7	98.7	98.7	98.3	90.6
	FP	65.8	66.0	67.3	73.3	64.0	77.3	76.0	72.0	70.2	
	LUD	98.0	96.7	98.7	99.3	100.0	100.0	100.0	100.0	99.1	
	PF100	88.6	88.0	88.0	88.0	88.0	88.0	88.0	88.0	88.1	
	TP	96.6	94.7	96.0	94.0	86.0	82.0	81.3	74.0	88.1	
	WEI	99.3	100.0	100.0	99.3	99.3	100.0	99.3	100.0	99.7	
WE	BVI	97.3	99.3	100.0	100.0	100.0	100.0	100.0	100.0	99.6	92.1
	FP	88.6	86.7	80.7	82.0	81.3	79.3	84.0	85.3	83.5	
	LUD	77.2	88.0	94.7	94.7	92.0	90.7	87.3	91.3	89.5	
	PF100	81.9	81.3	81.3	81.3	81.3	81.3	81.3	81.3	81.4	
	TP	96.0	97.3	97.3	99.3	100.0	100.0	100.0	100.0	98.7	
	WEI	100.0	100.0	99.3	100.0	98.7	99.3	100.0	100.0	99.7	
SE	BVI	98.7	98.7	99.3	98.7	98.7	98.0	98.7	99.3	98.7	96.6
	FP	85.9	98.0	95.3	90.7	91.3	92.0	93.3	95.3	92.7	
	LUD	89.3	84.7	95.3	94.7	98.7	100.0	100.0	100.0	95.3	
	PF100	94.6	94.0	94.0	94.0	94.0	94.0	94.0	94.0	94.1	
	TP	100.0	99.3	100.0	100.0	100.0	100.0	100.0	100.0	99.9	
	WEI	100.0	98.7	98.0	99.3	98.7	98.7	98.0	99.3	98.8	
EE	BVI	96.0	98.0	96.7	97.3	98.7	97.3	98.7	98.0	97.6	95.7
	FP	88.6	86.0	89.3	91.3	91.3	95.3	96.0	94.0	91.5	
	LUD	90.6	91.3	86.0	91.3	92.0	90.0	93.3	90.0	90.6	
	PF100	97.3	96.7	96.7	96.7	96.7	96.7	96.7	96.7	96.7	
	TP	98.7	98.0	96.7	96.7	99.3	100.0	100.0	100.0	98.7	
	WEI	100.0	99.3	98.7	98.7	100.0	100.0	99.3	99.3	99.4	
NE	BVI	98.7	100.0	98.7	98.0	95.3	95.3	97.3	95.3	97.3	94.5
	FP	94.6	88.0	88.0	88.0	85.3	87.3	82.0	89.3	87.8	
	LUD	99.3	98.0	99.3	100.0	100.0	100.0	100.0	100.0	99.6	
	PF100	85.9	85.3	85.3	85.3	85.3	85.3	85.3	85.3	85.4	
	TP	99.3	100.0	97.3	99.3	99.3	98.0	93.3	98.0	98.1	
	WEI	97.3	98.7	100.0	98.0	97.3	97.3	100.0	99.3	98.5	

Indicators:
- > BVI:– Biodiversity vulnerability index
- > FP:– Food production
- > LUD:– Land use diversity
- > PF100:– People flooded by 100 yr event
- > TP:– Timber production
- > WEI:– Water exploitation index

Regions:
- > EU:– Europe
- > WE:– Western Europe
- > SE:– Southern Europe
- > EE:– Eastern Europe
- > NE:– Northern Europe

Colour code of ranking % of significance:
- > 95% High
- 95 - 75% Medium
- < 75% Low

The results show that although most of the Europe-wide indicator-scenario combinations showed the lowest proportion (in comparison with the regional estimates) of future sectoral projections that are statistically significantly different from baseline estimates, there are significant regional differences. When considering all indicators and scenario combinations, about 91% of the indicator-scenario combinations at the European scale are statistically significantly different from their baseline equivalents. When comparing results across the sectors/sub-systems at the European scale, FP is identified as one with the least average percentage of the indicator-scenario combinations that are statistically significantly different values from its baseline estimate – with almost 30% of the combinations across all the scenarios having a statistically similar mean to the baseline estimate. This is followed by TP and PF100, both showing no/or very small differences from their baseline under some of the scenarios; with the overall proportion of the indicator-scenario combinations for each indicator reaching up to about 12% across all the scenarios (Table 6.1). In contrast, the WEI, LUD and BVI indices show the highest sensitivity with over 98% of their respective indicator-scenario combinations being statistically significantly different from their baseline estimates across all the climate scenarios. However, for the urban sector/sub-system, change in AS has no climate-driven sensitivity, and hence all the indicator-scenario combinations are found not to be statistically different from the baseline estimates.

In terms of the regional comparisons, when considering all the climate scenario combinations, southern followed by eastern Europe show the highest proportion of statistical significance – with over 95% of all the indicator-scenario combinations showing statistically significantly different estimates of indicators relative to their baseline values. This is particularly true for biodiversity, forestry and water sectors/sub-systems. Northern Europe follows with about 6% of the indicator-scenario combinations showing similar values to baseline estimates. However, western Europe is found to be with the most similar to baseline with the highest overall percentage (i.e., about 8% across all the climate scenarios). In addition, FP, LUD and PF100 in western Europe are found to be with the most similar to their baseline estimate than their respective estimate in other regions, while showing the highest percentage of statistically significantly different estimates (from baseline) in other regions including: FP in southern, PF100 in eastern, and LUD in northern Europe. In contrast, BVI, TP, and WEI show the least sensitivity in northern Europe, while experiencing significant changes in western (for BVI and WEI) and southern (for TP) Europe, respectively.

6.1.2 Due to socio-economic change scenarios

Table 6.2 presents a summary of the statistical significance analysis (based on a 5% significance threshold) considering effects of the socio-economic scenarios alone. Unlike the climate scenarios, when considering the runs based on the socio-economic change scenarios, the Europe-wide estimates show the highest percentage in comparison with the regional estimates – with about 95% of the indicator-scenario combinations being statistically significantly different from their respective baseline estimates. When comparing the European scale results across the sectors/sub-systems, PF100 is identified with the least percentage of the indicator-scenario combinations that are statistically significantly different from its baseline estimate – with almost 20% of the combinations having a statistically similar mean to baseline values. In addition, PF100 shows no change under the various GDP change related scenario groups (Table 6.2). The next least sensitive indicator is AS with about 13% of the combinations having similar estimate to baseline values – especially those estimated under the low-end scenarios with no/small change in population and GDP. In contrast, WEI, TP and LUD have the highest proportion (over 99%) of the indicator-scenario combinations with statistically significantly different estimates from their baseline values, followed by the BVI and FP.

Table 6.2: *European and regional average % of the number of indicator-scenario combinations that are statistically significantly different from baseline across the socio-economic scenarios.*

Regions	Indicators	Socio-economic scenarios grouped by GDP change (%)						All scenarios	All scenarios & sectors
		-20%	0%	50%	100%	150%	200%		
EU	AS	40.0	80.8	100.0	100.0	100.0	100.0	86.8	
	BVI	99.0	100.0	97.0	97.0	99.0	99.0	98.5	
	FP	100.0	99.0	100.0	97.0	98.0	98.0	98.7	
	LUD	98.0	100.0	100.0	99.0	100.0	98.0	99.2	94.7
	PF100	80.0	80.8	80.0	80.0	80.0	80.0	80.1	
	TP	99.0	100.0	99.0	100.0	100.0	100.0	99.7	
	WEI	99.0	100.0	100.0	100.0	100.0	100.0	99.8	
WE	AS	40.0	40.4	100.0	100.0	100.0	100.0	80.1	
	BVI	97.0	99.0	100.0	100.0	100.0	99.0	99.2	
	FP	97.0	97.0	100.0	98.0	99.0	100.0	98.5	
	LUD	97.0	96.0	98.0	98.0	95.0	95.0	96.5	93.3
	PF100	80.0	80.8	80.0	80.0	80.0	80.0	80.1	
	TP	99.0	100.0	100.0	100.0	100.0	100.0	99.8	
	WEI	100.0	99.0	99.0	97.0	99.0	100.0	99.0	
SE	AS	40.0	80.8	100.0	100.0	100.0	100.0	86.8	
	BVI	94.0	93.9	94.0	91.0	94.0	94.0	93.5	
	FP	97.0	97.0	96.0	99.0	97.0	99.0	97.5	
	LUD	99.0	98.0	98.0	93.0	94.0	93.0	95.8	93.3
	PF100	80.0	80.8	80.0	80.0	80.0	80.0	80.1	
	TP	100.0	100.0	99.0	100.0	100.0	100.0	99.8	
	WEI	98.0	99.0	100.0	100.0	100.0	100.0	99.5	
EE	AS	40.0	40.4	100.0	100.0	100.0	100.0	80.1	
	BVI	98.0	94.9	97.0	98.0	100.0	100.0	98.0	
	FP	96.0	100.0	100.0	97.0	99.0	100.0	98.7	
	LUD	96.0	96.0	99.0	99.0	98.0	97.0	97.5	92.6
	PF100	80.0	80.8	80.0	80.0	80.0	80.0	80.1	
	TP	99.0	99.0	94.0	92.0	89.0	92.0	94.2	
	WEI	99.0	100.0	100.0	100.0	100.0	100.0	99.8	
NE	AS	0.0	40.4	100.0	100.0	100.0	100.0	73.4	
	BVI	99.0	96.0	92.0	85.0	81.0	79.0	88.7	
	FP	97.0	96.0	95.0	97.0	96.0	96.0	96.2	
	LUD	99.0	99.0	99.0	99.0	99.0	98.0	98.8	89.9
	PF100	40.0	80.8	80.0	80.0	80.0	80.0	73.5	
	TP	100.0	100.0	98.0	100.0	100.0	100.0	99.7	
	WEI	100.0	99.0	100.0	97.0	99.0	100.0	99.2	

Indicators:
- AS:– Artificial surfaces
- BVI:– Biodiversity vulnerability index
- FP:– Food production
- LUD:– Land use diversity
- PF100:– People flooded by 100 yr event
- TP:– Timber production
- WEI:– Water exploitation index

Regions:
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- EE:– Eastern Europe
- NE:– Northern Europe

Colour code of ranking % of significance:
- >95% High
- 95 - 75% Medium
- <75% Low

When comparing the regional estimates, both western and southern Europe show the highest proportion of statistical significance with only about 7% of the indicator-scenario combinations have similar mean to baseline estimates – TP and WEI show the highest, while AS and PF100 showing the least proportion of the combinations with mean values similar to baseline estimates. The second highest proportion is eastern Europe with just over 92% of the indicator-scenario combinations having statistically significantly different mean indicator estimates to baseline values. In contrast, northern Europe is with the highest proportion (over 10%) of the combinations showing similar mean to baseline estimates – AS and PF100 showing the lowest proportion than any other sector/sub-system and region with about 27% of the indicator-scenario combinations showing similar mean estimates to baseline values.

6.1.3 Due to combined climate and socio-economic change extreme scenarios

Figure 6.1 presents a summary of the statistical significance analysis (based on a 5% significance threshold) considering 8 extreme scenario combinations, including (1) climate drivers-only (CD-L and CD-H), (2) socio-economic drivers-only (SED-L and SED-H), and (3) combined climate and socio-economic drivers (C&SED-L/L, C&SED-L/H, C&SED-H/L, and C&SED-H/H) (Note: L and H represent the lower and upper uncertainty ranges of the various climatic and socio-economic drivers considered; Section 4.5.1).

The results show that except for AS (in all regions) and European level FP, all (100%) of the indicator-scenario combinations have future estimates that are statistically significantly different from the baseline in all regions. Those indicator-scenario combinations that are found not to be statistically different from their baseline estimates are related to AS (under the CD-L and CD-H scenarios, as it has no climate-driven sensitivity in all regions) and FP (at the European scale under the CD-L scenario).

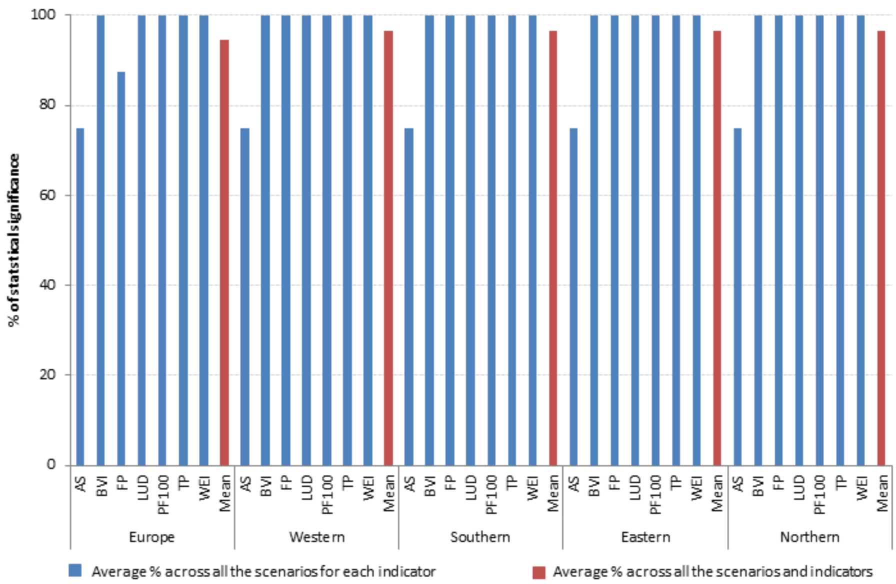


Figure 6.1: *European and regional average % of the number of indicator-scenario combinations that are statistically significantly different from baseline across the extreme climate and socio-economic scenarios.*

The following sections present the results of a systematic analysis of the key sensitivities and uncertainties of future cross-sectoral impacts in Europe. The analysis is based on the multiple-drivers-at-a-time (MDAT) scenario and uncertainty analysis approach considering the various MDAT scenario combinations (e.g., CD, SED, C&SED-scenarios)[22]. Importantly, the approach used draws from two types of analysis based on: (i) a sensitivity analysis of the selected impact indicators to changes in multiple climatic and socio-economic drivers considering the 'full' ranges of MDAT climatic and socio-economic scenarios considered (see Section 4.5), and (ii) uncertainty analysis and ensemble-based simulations for future projections of the cross-sectoral impacts considering a set of 'not-implausible' ranges of climate and socio-economic scenarios (Section 6.6) selected from the future MDAT scenario space (Figure 4.5 and Section 4.5.3).

The analyses allowed, (1) by considering the full ranges of the MDAT scenario space, to: (i) highlight the extremes in future cross-sectoral impact sensitivities due to changing conditions (Section 6.2) and (ii) identify the key area-aggregate sensitivity trends (Sections 6.3.1 and 6.4.1) and statistical distribution of the grid-based future changes and the contributions of the various climatic and socio-economic drivers to the overall sensitivities of the key impact indicators investigated (Sections 6.3.2–3 and 6.4.2–3); and (2) by considering the selected 'not-implausible' sample scenario ranges, to: (i) provide ensemble-based plausible future projections and (ii) quantify potential uncertainties of the future changes in the area-aggregate (Sections 6.7.1 and 6.8.1) and grid-based spatial distribution (Sections 6.7.2 and 6.8.2) of the cross-sectoral impacts at the European and regional scale under the various future climate and socio-economic scenarios. The results illustrate that there are significant variations in the overall sensitivities and uncertainties of the cross-sectoral impacts across the sectors, regions, and scenarios as discussed in the following sub-sections.

6.2 Extremes of Cross-Sectoral Impact Sensitivities due to Changing Conditions

With the growing interest in understanding the potential implications of, what are commonly referred as, 'high-end' scenarios (e.g., the ongoing EU FP7 HELIX, IMPRESSIONS and RISES-AM-projects), consideration of the 'full ranges' of the MDAT scenarios (including the extremes) provides important insights into the potential cross-sectoral implications of the 'less likely' but extreme scenarios, as represented by some of the MDAT scenarios investigated here. Sections 6.2.1 and 6.2.2 present summaries of the extreme ranges (minimum and maximum) of the

[22] See Figure 4.5 for details on the MDAT scenario and uncertainty analysis methodology and descriptions of the scenarios.

percentage change of the indicators from baseline across the full ranges of the MDAT scenarios at the European and regional scales, respectively.

6.2.1 European scale sensitivity summaries

Figure 6.2 presents the European scale summary of the extreme minimum and maximum changes of the different sectoral indicators from baseline across the various climate, socio-economic, and combined climate and socio-economic scenarios. The results show that at the European scale, all sectors/sub-systems (except urban) are projected with both an increase and a decrease in the indicators values from their respective baseline estimates across the various scenario classes.

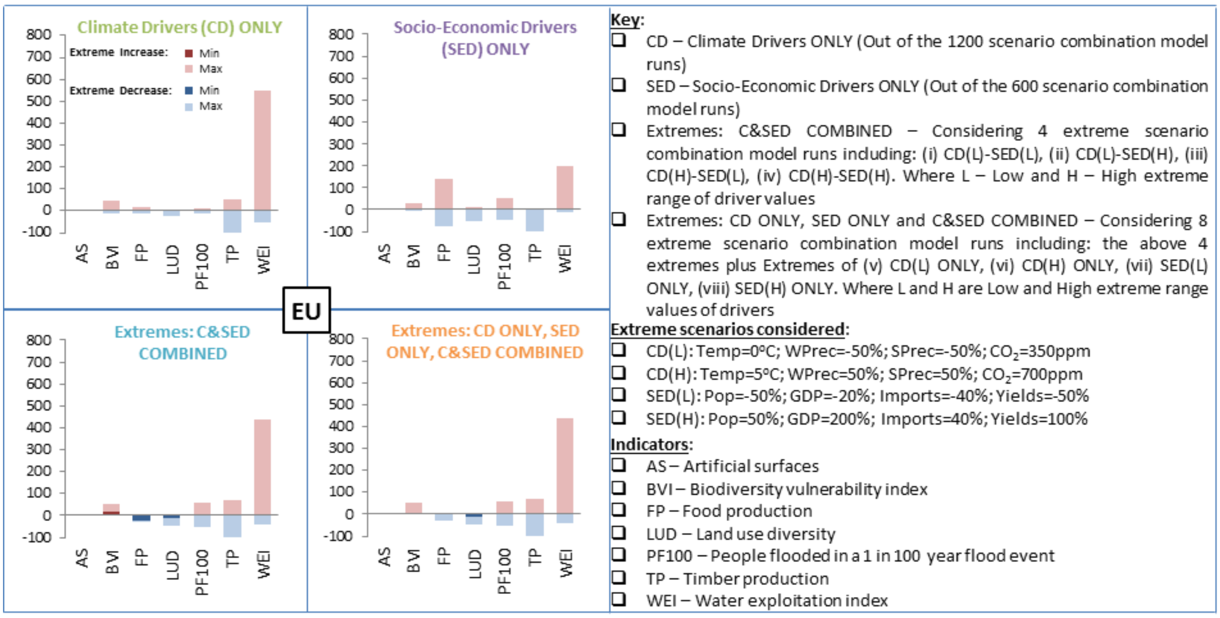


Figure 6.2: *The European extreme minimum and maximum % change (from baseline) of indicators across the 'full ranges' of the MDAT scenario combinations investigated (see Figure 4.5).*

The urban sector (i.e., AS) shows no change under the CD-scenarios as it is not sensitive to climatic factors (Section 5.1.1). Conversely, under the SED-scenarios, AS generally shows a robust (increase-only) trend, especially under the extreme scenarios with high increase in GDP. The highest scenario leads to an overall increase in AS by about 3.3% from the baseline proportion of urban areas covered by residential and non-residential surfaces. In comparison with other sectors, these changes are relatively small.

However, WEI both increases and decreases depending on the scenarios. When compared against all other sectors/sub-systems, WEI also shows the highest sensitivity in terms of the percentage change from baseline under all the scenario groups considered. Under the CD-scenarios, the percentage sensitivity range is estimated at about 600%, mainly leading to a significant increase in Europe-wide water stress, except under some climate scenarios with high increase in precipitation (which leads to a decrease in WEI by up to 50%; see Figure 6.2). On the other hand, when the SED-scenarios are considered – the sensitivity range drops almost by a third to just over 215% change from the baseline. These changes highlight that the direct and indirect effects of the socio-economic drivers (e.g., population and GDP change) are relatively smaller when compared with the climate change drivers (e.g., temperature and precipitation change). In addition, the higher percentage change in WEI from the baseline under the two sets of extreme scenario groups is also mainly attributed to the effects associated with the climate drivers. The sensitivity range under these extreme scenarios is also estimated between a 40% decline under the low-end scenarios and a 436% increase under the high-end scenarios.

Following WEI, FP is estimated with the second highest sensitivity range of about 213% change from the baseline under the SED scenarios. However, under the CD-scenarios the estimated FP has a range of just over 30% only (i.e., ranging between a 12% decline and a 19% increase from baseline across the scenarios). This also highlights that socio-economic drivers (particularly population and food imports) play a key role in the Europe-wide future food security challenges. However, under the extreme combined C&SED-scenarios, FP decreases by about 31% from the baseline, also highlighting the complex interactions of impacts of climatic and socio-economic drivers on future food demand and the uncertainty on how this growing demand can be met in the future. In addition, the slightly higher percentage changes under the extreme scenarios are also mainly attributed to changes in the socio-economic drivers; especially the decline in FP is associated with those scenarios with a decline in population combined with increase in food imports leading to a decrease in food demand, and hence production. These sensitivities and uncertainties in future changes in agricultural land use and FP have important implications on other sectors/sub-systems that are affected by land use changes. For example, TP shows a mainly decline-only trend (with only a 0.5% increase under some scenarios) with almost a 100% loss of forest areas from baseline under most of the SED-scenarios. This is mainly associated with the indirect effects of land use changes for FP, where for example, an increase in a European population leads to an increase in FP to meet the new demand, and hence forest area being replaced by agriculture (e.g., intensive farming such as arable or grassland), resulting in a decline in overall TP. This is also illustrated in the combined extreme C&SED-scenarios with the maximum range reaching up to 170% (i.e., a range between a 100% decline and 70% increase in TP from baseline). However, when CD-scenarios are considered, there is a projected increase in TP by up to 52%, especially under those scenarios with higher CO_2 emission levels resulting in improved productivity for timber production in some areas. Moreover, the complex changes in land use also have important implications on LUD – with the highest sensitivity estimated due to the SED-scenarios with a range of 64% (i.e., between -53% and +11% from baseline). In contrast, when the combined C&SED-extreme scenarios are considered, LUD shows a robust trend across all the scenarios, declining by up to 35% from the baseline.

In contrast, PF100 shows higher sensitivity to changes in socio-economic drives than climatic drivers, as illustrated by a sensitivity range of up to 112% (i.e., between a 55% decline and 56% increase from baseline) under the SED and extreme (SED-related) scenarios. These are mainly associated with those scenarios with a European level increase in population, resulting in an increase in the potential number of people living in (river and coastal) floodplains. In contrast, when the CD-scenarios are considered, the percentage change in PF100 varies between just -14% and +8% (from the baseline) – and these sensitivities are associated with those scenarios with declining and increasing precipitation, respectively.

The BVI also shows marginal Europe-wide sensitivity under the various scenario groups (Figure 6.3). The highest change in BVI is observed under the CD-scenarios with a sensitivity range of 56% (i.e., between a 43% increase in biodiversity stress and a 13% improvement in vulnerability). Although there are regional variations (as discussed below), the Europe-wide sensitivity is mainly attributed to scenarios with significant temperature and precipitation changes, with the hot-and-dry scenarios leading to an increase in BVI, while the extreme wet scenarios leading to some level of improvement in vulnerability. In addition, the socio-economic change drivers also have an indirect effect on biodiversity through land use changes associated with FP affecting those species related to arable farming. For example under the SED-scenarios, BVI increases by 30% from baseline, with only very small (<0.1%) improvement in vulnerability under some scenarios. Also, a sensitivity range of 22% and 46% change in BVI from the baseline is estimated under the two extreme scenario groups, respectively.

6.2.2 Regional scale sensitivity summaries

When the aggregated regional impacts and sensitivities are considered, there are significant variations across the sectors/sub-systems, regions and scenarios (Figure 6.3). The results show that depending on the projected percentage change of the various drivers within the scenarios, all sectors/sub-systems are estimated to increase and/or decrease under part or all of the different scenario groups. The exception is the urban sector/sub-system, which is sensitive to socio-economic drivers only (i.e., related to the SED or SED-related extreme scenarios), and there are no climate-driven changes in AS. In addition, urbanisation is projected to always increase (robust trend) from the baseline estimate under all the SED-related scenarios considered. The highest urban growth is estimated in western Europe, with up to 7% increase in AS from the baseline. This is followed by a 3% growth both in southern Europe and at the European scale, while the least changes are observed in eastern and northern Europe with just 1% increase from baseline. These changes have implications on other sectors/sub-systems, and a cross-sectoral comparison of the results in each region is discussed below.

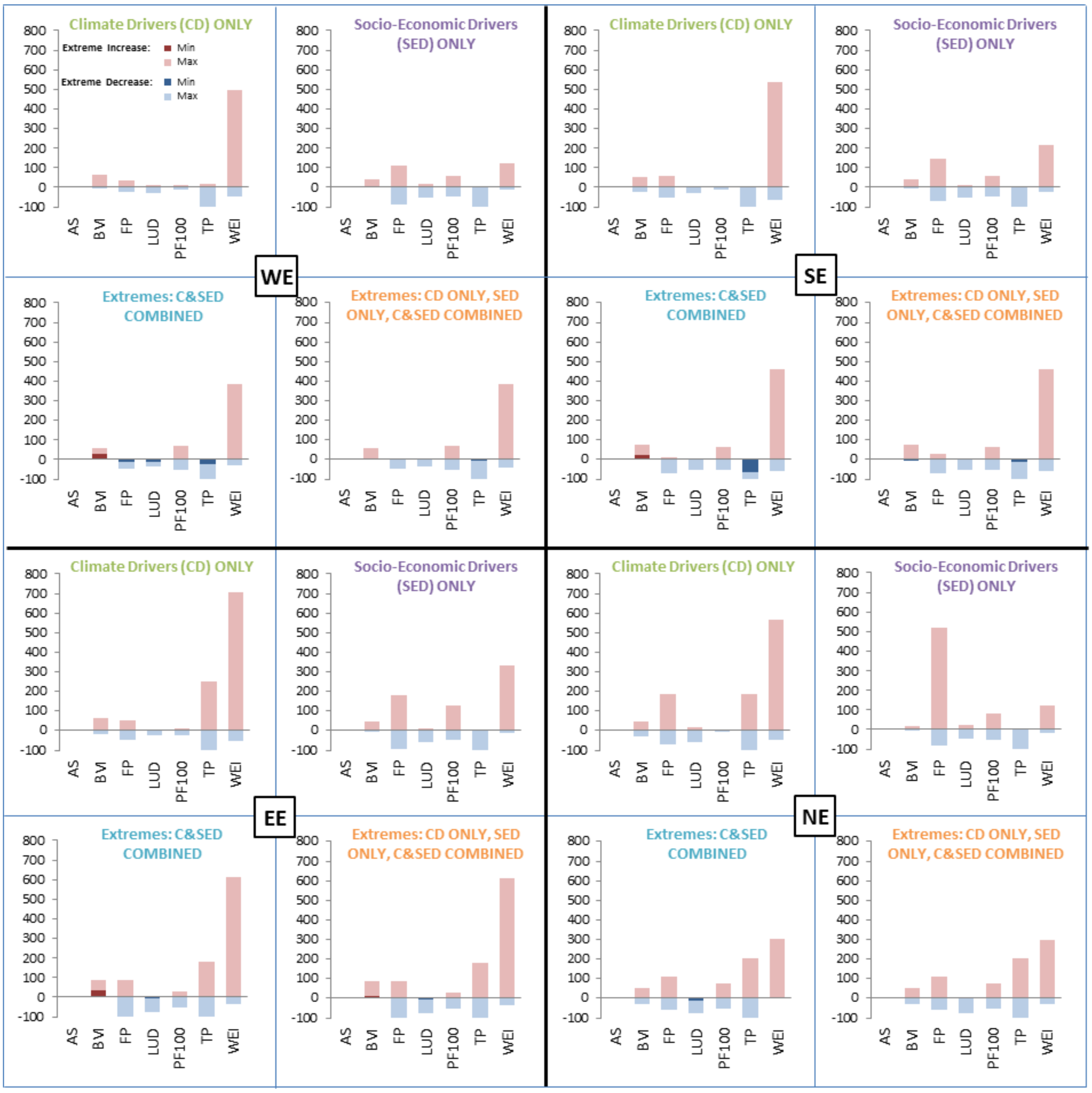


Figure 6.3: *The regional extreme minimum and maximum % change (from baseline) of indicators across the 'full ranges' of the MDAT scenario combinations investigated (see Figure 4.5). See Figure 6.2 for abbreviations used in the graphs.*

In western Europe, WEI and PF100 show variations in terms of the directions of change (both increasing and decreasing from baseline under the different scenario groups). However, other indicators show robust trends under some scenarios, especially the extreme scenarios including the combined climate and/or socio-economic (extreme CD, SED or C&SED) scenarios (Figure 6.3). For example, AS and BVI are projected to have an always-increasing (robust positive) trend (each increasing by up to 7% and 51%, respectively). In contrast, TP, FP and LUD are all projected to have an always-declining (robust negative) trend under the C&SED-extreme scenarios, with the highest estimated regional level changes from the baseline reaching up to -94%, -47% and -33%, respectively. In terms of the cross-sectoral comparison of the magnitudes of change, WEI is identified as the most sensitive indicator with a sensitivity range in the percentage change from baseline estimated between 418% (i.e., -31% to +387%) and 544% (i.e., -47% to +497%) under the CD-scenarios and the extreme scenarios, respectively. In contrast, under the SED-scenarios FP is estimated with the highest sensitivity range of 201% (i.e., between a 91% decline and +110% increase from the baseline under different SED-scenarios), and it is followed by WEI with sensitivity range of 133%. However, when the extreme scenarios are considered, next to WEI, PF100 is estimated with the second highest sensitivity range of 123% (with almost equal percentage of change – both increasing and decreasing from baseline under the different scenarios). BVI also shows marginal sensitivity across the scenarios. Except under the CD-scenarios (where some scenario combinations with an increase in precipitation and decrease in temperature lead to a slight improvement in vulnerability by up to 3% from baseline), there is a robust (always increasing) trend in the overall stress on biodiversity in the region across the scenarios. The sensitivity ranges for BVI in the region are estimated at 66%, 57% and 39% under the CD, the extremes, and SED-scenario groups, respectively (see Figure 6.3).

In southern Europe, the urban sector/sub-system again shows no change under the CD-scenarios and an increasing-only (robust) trend under the SED (and SED-related extreme) scenarios, reaching up to a 3% growth in the proportions of artificial surfaces in the region. On the other hand, except under the SED-scenarios (in which there is a very small, less than 1%, increase), TP generally shows a robust (declining-only) trend. Similarly, BVI and LUD show robust trends under the C&SED-scenarios, with the sensitivity ranges estimated at +74% (increase-only) and -54% (decrease-only), respectively. In terms of the magnitudes of change, WEI is projected with the highest sensitivity range under all the scenario groups, with the highest projected change from baseline estimated at a 536% increase in water stress (from baseline) under the CD-scenarios. FP shows the second highest sensitivity with a 147% increase and 68% decline (the highest decline than in other regions) from baseline under different scenarios within the SED-scenarios. There is also a significant decline (by up to 70% from baseline) in FP under the extreme scenarios. On the other hand, PF100 both increases and decreases equally under across the scenarios – with the highest sensitivity range reaching up to 118% change from baseline under the SED-related scenarios.

In eastern Europe, all sectors/sub-systems show both increase and decrease in impacts across most of the scenarios. The exceptions are AS (always increasing under all scenarios), BVI (also with increase-only trend under all extreme scenarios) and LUD (with decrease-only trend under the C&SED-extreme scenarios) (Figure 6.3). In terms of the magnitudes, WEI followed by TP is again the most sensitive indicator, especially under the CD-scenarios: with a maximum increase from baseline by 707% in WEI (which is the highest percentage increase than any other sector/sub-system or region) and by 253% in TP (also the highest increase in TP than in other regions). This is followed by FP with a sensitivity range of 275% change (with a +179% increase and -97% decrease (the highest decline than any other region) from baseline) under the SED-related scenarios, followed by a 185% sensitivity range under the extreme scenarios. PF100 also shows the highest sensitivity in flood impacts than in other regions, especially under the SED-related scenarios with a range of up to 179% change (i.e., between a 50% decline and 128% increase from the baseline). In addition, although there is some improvement (i.e., 20% decline under the CD-scenarios) in vulnerability, BVI also increases by up to 75% from baseline under the combined extreme scenarios, which is the highest increase in vulnerability when compared with other regions. This is attributed to both the direct impacts of the climatic drivers (under the hot-and-dry scenarios) and indirect effects of the socio-economic drivers (associated with those scenarios that lead to a decline in arable farming which affects those arable-related species) resulting in an increase in the overall vulnerability in biodiversity (e.g., de Chazal and Rounsevell 2009).

In northern Europe, there are improvements in most sectors/sub-systems. Except AS (again increase-only trend) under all scenarios and LUD and WEI (decrease-only and increase-only trends, respectively) under the C&SED-extreme scenarios, all sectors/sub-systems are projected to both increase and decrease from baseline under the different scenarios. However, in terms of the magnitudes of change WEI (under the CD-scenarios) and FP (under the SED-scenarios) are the highest sensitive indicators, with an estimated range of more than 600% (i.e., between -46% and +567% change in WEI and -82% and +519% change in FP). The increase in the regional total FP is the highest percentage increase from baseline than in other regions in Europe, which also reflects the potential north-ward shift and increase in agriculture under changing future socio-economic factors (e.g., increasing population) to meet the consequent growth in demand for food production. Under the CD and C&SED- extreme scenarios, FP is also projected with a significant increase from the baseline with a sensitivity range between 173% and 256% across the scenarios. Timber production also shows high sensitivity with a significant increase under most of the scenarios, especially under the CD (and CD-related extreme) scenarios resulting in a 204% increase from the baseline. This is mainly due to improved productivity under some of the scenarios associated with higher CO_2 level. These changes in agricultural and forest land use have implications in LUD, which result in the highest sensitivity, with the highest increase (by about 25% under the SED-scenarios) and the highest decrease (by 77% under the extreme scenarios) from baseline than in other regions. The number of people flooded (PF100) also shows high percentage increase from baseline, with a sensitivity range of 131% (with up to 81% increase from baseline) under the SED-scenarios. On the other hand, the highest (of all regions) regional improvement in biodiversity vulnerability is observed in northern Europe under the CD-scenarios, estimated with up to a 32% decrease in BVI from the baseline. This is also attributed mainly to the north-ward shift in some species as the north becomes more appropriate for some species from the south under warmer climate.

However, focussing only on the extremes based on the scenario groups hides a better understanding of the sensitivity distribution and identifying which factors (climatic and/or socio-economic) are important. Hence, the analysis results are discussed in more detail in the following sub-sections considering both the regional aggregated sensitivity trends and spatial distribution of the impacts focussing on changes in grid-cell value of the indicators under each driver and scenario groups independently.

6.3 Sensitivity of Cross-Sectoral Impacts due to Climate Change Scenarios

This section presents (i) a sensitivity analysis of the trends in future changes of the area-aggregate cross-sectoral impacts at the European and regional scale (Section 6.3.1), and (ii) the percentile distribution of the grid-based changes in the indicators across Europe and the four catchment-based regions (Section 6.3.2) under the full ranges of MDAT climate change scenarios.

6.3.1 Area-aggregate impact sensitivity trends at European and regional scales

Figure 6.4 presents the effect of individual drivers and aggregated summary of the sensitivity trends for each sectoral indicator under the various scenario combinations grouped based on changes in temperature (at every $1^{o}C$ increase from baseline) and CO_2 concentration (at a 50ppm increase from current levels). The results show that WEI and TP show the highest sensitivity, while PF100 has the least sensitivity. In comparison, WEI particularly in eastern Europe has the highest change, by up to almost 200% increase from baseline. This is the highest increase than any other sector/sub-system and region, with a steep positive indicator-driver trend and associated increase with an increase in temperature (especially under the current level of CO_2 concentration) (Figure 6.4). Although the effects of change in CO_2 concentration are generally less pronounced, there are similar positive trends in WEI in all regions, in relation to an increase in temperature. This is especially true at the European scale as well as in southern and western Europe. However, in southern Europe there is a small decline in the rate of change in WEI under the scenarios with higher temperature change from baseline. In contrast, in northern Europe the effect of temperature on water stress is varied with less/no sensitivity to lower changes in temperature (up to about 3°C), and showing a significant change (reaching up to 84%) from its baseline estimate under the high-end scenarios.

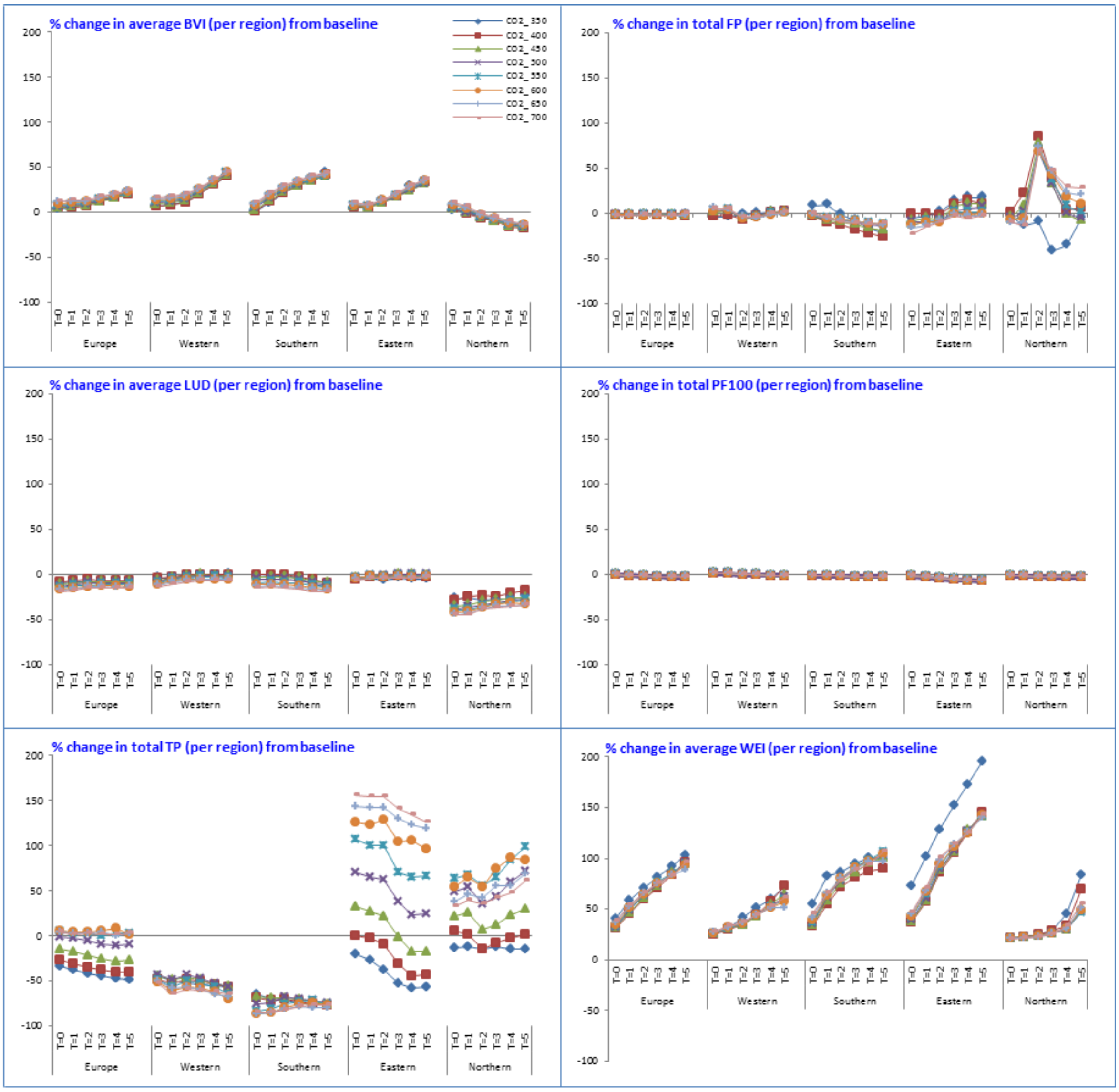


Figure 6.4: *Sensitivity of impacts based on the % change in indicators (from baseline) for Europe and the four regions under the 'full' ranges of climate change MDAT scenarios grouped by change in temperature and CO_2 concentration. NB: Each data point represents an ensemble mean % change of 25 scenarios of combined change in winter and summer precipitation – see the full MDAT sensitivity summary in Appendix C.*

In contrast, when compared with WEI the effect of temperature change on TP is relatively small (with mainly declining trend with increasing temperature) in terms of region-by-region comparison between the two sectors/sub-systems. TP is more sensitive to changes in the level of CO_2 concentration, especially in eastern Europe – increasing with increasing CO_2 level. The highest increase in TP is estimated at 156% (eastern Europe) under the 700ppm CO_2 emission scenario. In northern Europe, TP also increases by up to 99% (under the scenario with a 550ppm CO_2 level and highest temperature rise), while there is only an 8% increase at the European scale. However, there is an overall agreement in terms of the directions of change in TP in some regions under most scenarios, with a consistent decline in TP from the baseline. This is particularly the case in southern and western Europe (under all scenarios), as well as at the European scale (under most scenarios, except those with high CO_2 level) and in northern Europe (at lower CO_2 level scenarios). The highest decline in regional TP is projected in southern Europe with an estimated value of about 87% loss from baseline, followed by a 71% decline in western Europe.

Following WEI and TP, BVI also shows a moderate sensitivity change from the baseline with an overall increasing trend with temperature increase (with relatively small/no effect due to change in CO_2 level) in all regions. The exception is northern Europe, where there is some improvement in vulnerability under some scenarios with increasing temperature that lead to a south-to-north shift in some species. The highest change in BVI is estimated in western and southern Europe with up to a 45% increase from baseline. In contrast, FP and LUD show only marginal sensitivities under most scenarios in all regions. The exception for both is in northern Europe, where LUD shows a decrease-only trend under all the scenarios resulting in a decline in diversity between 17% and 45%. Conversely, FP increases under most scenarios peaking at 85% under a $2^{o}C$ temperature change, while declining by up to 42% under the 350ppm CO_2 level with a $3^{o}C$ increase in temperature. In contrast, PF100 is less/not sensitive to changes in both temperature and CO_2 emission levels, in all regions, except in eastern Europe with a small (just 7%) decline from baseline under the high-end scenarios.

The effect of precipitation change on all indicators in combination with temperature change under various scenario combinations are illustrated using sensitivity summary surface charts, which are presented for each indicator as discussed below. Focussing on combined changes in annual temperature and precipitation under two CO_2 emission levels (i.e., 350ppm at baseline and extreme future scenario of 700ppm), the remaining parts of this section presents the European and regional sensitivity trends of impacts under the full ranges of the MDAT climate change scenarios for each indicator.

Artificial surfaces

At the baseline, the area-average % of AS is estimated at 3.7% for the whole of Europe, while the regional estimates are 6.5% (western), 4.1% (eastern), 3% (southern) and 1.2% (northern) Europe respectively (Sections 5.1.1 and 5.2.1). However, future urban growth is driven only by changes in socio-economic drivers, and hence the climate change drivers considered here have no effect on AS. The sensitivities due to changes in the socio-economic drivers investigated are discussed in Sections 6.4.

People flooded in a 1 in 100 year flood event

Figure 6.5 presents sensitivity of the European and regional scale PF100 under different climate change scenarios. The results are summarized considering changes in annual temperature (0 to 5^{o}C) and precipitation (-50 to +50%) under the current (350ppm) and future (700ppm) CO_2 emission levels. (Note that the effect of the main climate change driver for flooding (i.e., sea-level rise) is presented in Section 5.1.1, and is not included here). At the baseline, the European scale PF100 is estimated at approximately 17.4 million people. Considering future changes under the full ranges of scenarios, the sensitivity of PF100 is moderately small, when compared with other sectors/sub-systems. The results show that PF100 has a positive correlation with change in precipitation (i.e., PF100 increases with increase in precipitation) and negative correlation with temperature change (i.e., PF100 decreases with increasing temperature), although with varying magnitudes and regional variations. Note that under the current flood modelling approach used in the CLIMSAVE IAP, there is no distinction between the impacts of precipitation due to seasonal variations, as PF100 is only sensitive to the magnitudes of change in precipitation regardless of the seasonal changes, as illustrated in the sensitivity summary plots in Figure 6.5. In addition, the results under the two extreme CO_2 emission scenarios show that PF100 is not sensitive to changes in CO_2 concentration.

Depending on the scenarios, the sensitivity of PF100 at the European scale ranges between a 14% decline from the baseline under the extreme hot-and-dry scenario (with a 5^{o}C rise in temperature combined with a 50% decline in precipitation) and an increase by over 8% under the high (i.e., extreme wet scenario with a baseline temperature combined with a 50% increase in winter and summer precipitation).

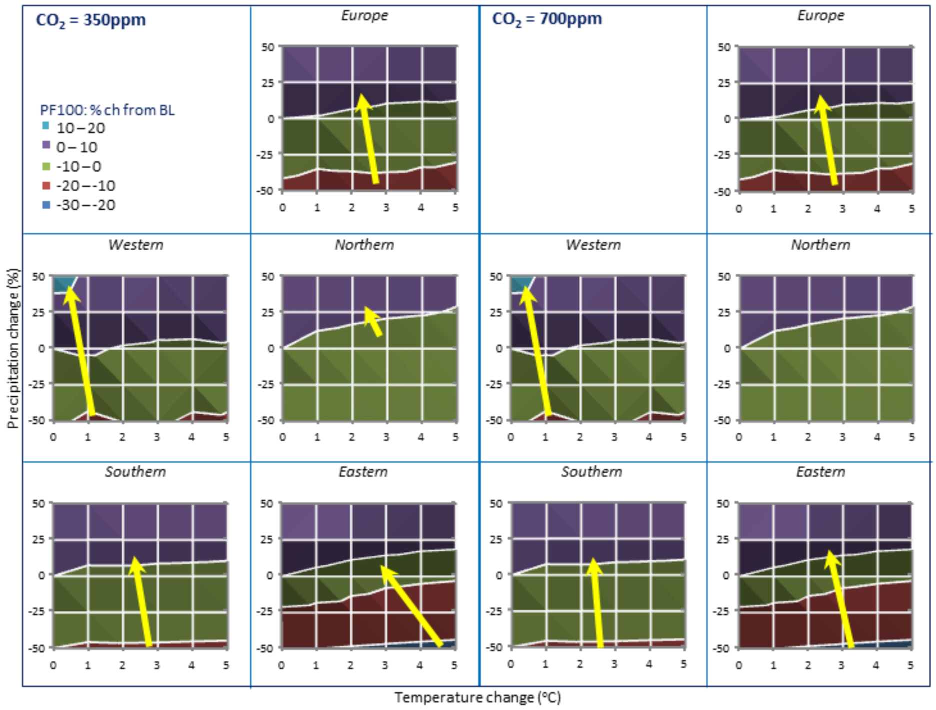


Figure 6.5: *Sensitivity of the % change in number of people flooded due to changes in temperature versus precipitation under baseline and future emission scenarios. Arrows show increasing trends (direction) and % change ranges (length).*

However, when looking at the regional aggregated estimates, although western Europe has the highest PF100 at the baseline (with almost 8.3 million people) (Table 5.2), the highest sensitivity in future impacts is observed in eastern Europe with a range between -22% and +10% of change in PF100 from baseline (which is estimated over 4.6 million people); followed by western Europe (ranging between -12% and +11% from the baseline) and southern Europe (between -11% and +4%;Figure 6.5). The baseline PF100 in northern Europe are estimated the lowest (with about 1.1 million people flooded) when compared with other regions. The future estimates also show the least sensitivity to changes in the climate drivers with a range between just about -7% and +2% change in PF100 across the full ranges of scenarios investigated.

Land use-related indicators: food production, timber production and land use diversity

The land use allocation model uses a series of regression calculations (with up to ten iterations) to determine the final proportions of rural land allocation and FP based on relative profitability (e.g., of crops and timber) and food demand (Audsley *et al*. 2015). As highlighted in Chapter 3, in the current modelling system, the farm model uses autonomous adaptation to prioritise food production through expanded agricultural land allocation for food sufficiency (also taking into account food imports) to meet the European scale food demand. This means that any driver that has an impact on food demand or agricultural production has a considerable impact on all other sectors/sub-systems that are dependent on land use, such as the forests and biodiversity sectors/sub-systems.

Although there are regional variations in terms of both the magnitude and directions of change, in comparison, FP at the European scale is less sensitive to the various climate scenarios including the 350ppm and 700ppm CO_2 emission levels (Figure 6.6 and Appendix C). Considering the climate-only (CD) scenarios (with baseline SED settings, including no change in the amount of food imported from outside Europe), these results also demonstrate the importance of food security as a key issue driving the future of European land use and the central importance of land use in decision-making across all natural resource sectors/sub-systems. It also illustrates that the modelling system is generally able to maintain FP to meet European demand under most of the various changed-scenarios, which often comes at the expense of other sectors/sub-systems, such as forests. However, under the extreme climate scenarios, the sensitivity in European level FP ranges between a 12% decline (under a scenario with a 650ppm CO_2 emission, 5^{o}C temperature rise, and a 50%/25% decline in winter/summer precipitation, respectively) and a 19% increase (under a scenario with a 650ppm CO_2 emission, 2^{o}C rise in temperature, and a 50% decline in summer precipitation) from baseline. Under the combined changes in temperature and precipitation, the sensitivity range at the European scale are estimated only between -4% and +1% (under 350ppm CO_2 emission) and -5% and +2% (under 700ppm CO_2 emission) (Figure 6.6).

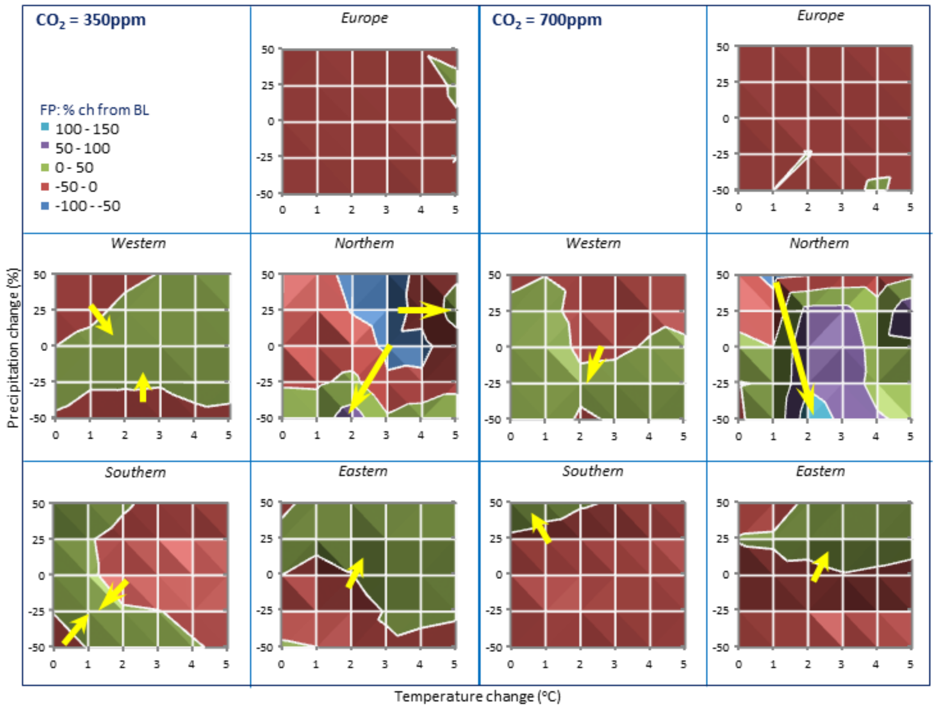


Figure 6.6: *Sensitivity of the % change in food production due to changes in temperature versus precipitation under baseline and future emission scenarios. Arrows show increasing trends (direction) and % change ranges (length).*

Considering the regional aggregated estimates, FP is highest in western Europe, followed by southern and eastern Europe (Appendix C). Although with the least FP at the baseline, northern Europe is projected to experience the highest sensitivity under the climate scenarios, with FP notably declining under some of the scenarios (ranging between -69% and +74% at baseline emission level and between -62% and +126% under future emission scenario). Southern Europe is also identified as with the next highest sensitivity (ranging between -48% and +35% change from baseline). In western Europe, on the other hand, FP shows the least sensitivity to change in the climate drivers. This illustrates the general expansion of agricultural land use across Europe, particularly to areas where productivity becomes higher, in order to meet the existing European food demand, while productivity in other areas (e.g., in southern Europe) declines under some of the climate scenarios.

As discussed above, the prioritization of land use for food production in Europe is highlighted by the projected decreases in TP due to a significant decline in forest areas across Europe as a result of agricultural land area expansion under most of the scenarios. This is consistent with other previous land use scenario studies (e.g., Rounsevell *et al*. 2006), which suggested that changes in forest areas largely result from changes in other land uses, such as agriculture. Figure 6.7 presents the sensitivity of TP to changes in temperature and precipitation (with baseline and future CO_2 emission levels) in Europe and the four regions considering different scenario combinations. Under the 350ppm CO_2 emission level, there is a significant decline in TP both at the European scale as well as in western and southern Europe – with a sensitivity range between -100% and +13%. However, under the 700ppm CO_2 emission level, there is a significant increase in TP under some scenarios, particularly in eastern (by up to +220%) and northern Europe (by up to 81%). This increase is mainly attributed to the improved forest growth and timber productivity with increase CO_2 levels.

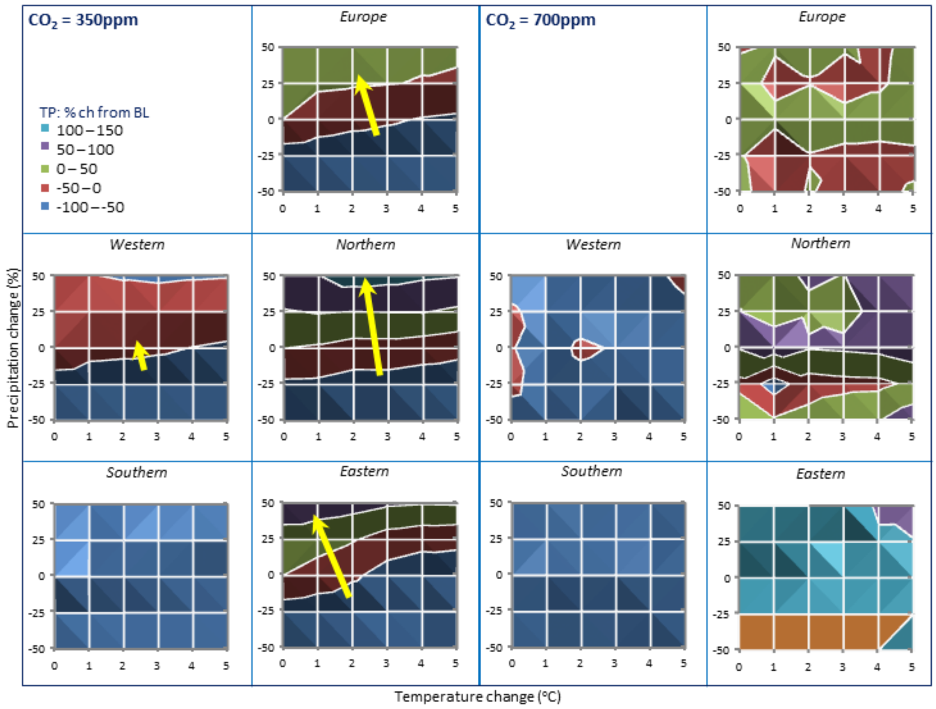


Figure 6.7: *Sensitivity of the % change in timber production due to changes in temperature versus precipitation under baseline and future emission scenarios. Arrows show increasing trends (direction) and % change ranges (length).*

These changes in agricultural and forest land areas also have significant implications on land use diversity as illustrated in the complex sensitivity patterns (Figures 6.6 and 6.7). At the European scale, LUD shows an overall decrease under all the scenarios – declining by up to 19% (under baseline CO_2 emission level with a 4^{o}C temperature and 50% precipitation increase) and 24% (under the future emission scenario with a 50% increase in precipitation).

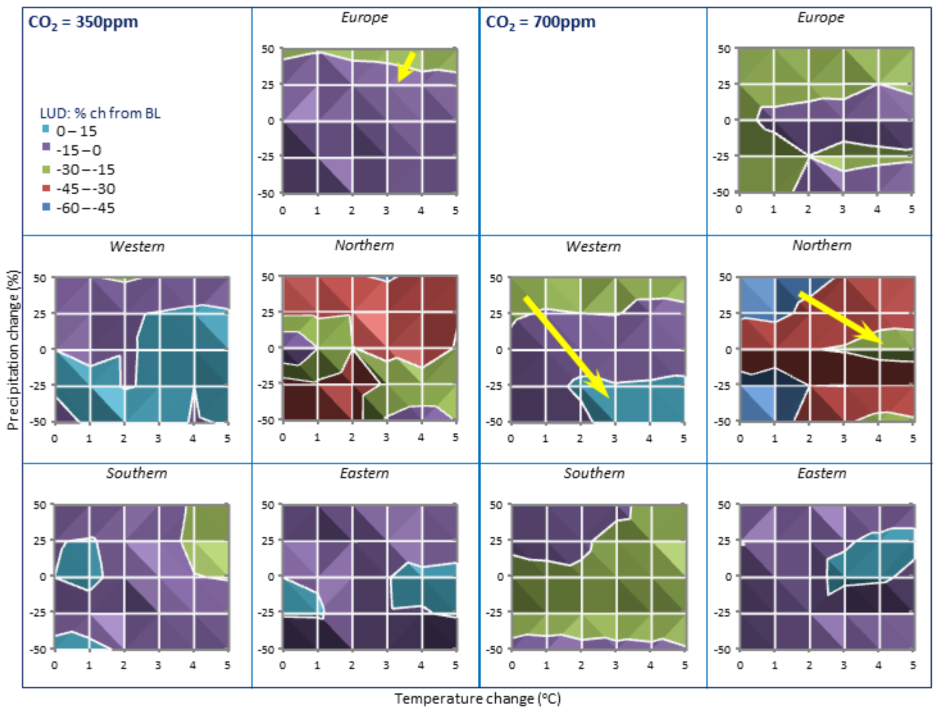


Figure 6.8: *Sensitivity of the % change in land use diversity due to changes in temperature versus precipitation under baseline and future emission scenarios. Arrows show increasing trends (direction) and % change ranges (length).*

In terms of the regional changes under the baseline CO_2 emission level, LUD also shows a declining-trend from baseline in all regions, especially in northern Europe declining significantly by up to 47%. This is followed by southern Europe with up to a 24% decrease from baseline, while projected with a small (about 5%) increase in western Europe under the 5^{o}C increase in temperature. When the 700ppm CO_2 emission scenario is considered, the highest decline in LUD is again projected in northern Europe (with up to 58% decline from baseline under some scenarios), followed by a 27% decline in western Europe (although some scenarios have a positive effect with a maximum of 3.5% increase from baseline).

Water exploitation index

When compared with other sectors/sub-systems, WEI shows the highest sensitivity to changes in the climatic drivers across almost all scenario combinations. For example at the European scale, the percentage change (from baseline) in WEI is estimated between -46% and +546% under the 350ppm CO_2 emission level and between -50% and +490% under the 700ppm CO_2 emission scenario (Figure 6.9). When comparing the effects of individual drivers, the higher sensitivity of WEI is mainly driven by change in precipitation (with a clear trend and negative correlation – WEI decreasing with increasing precipitation). In contrast, WEI is less sensitive to temperature change (with positive correlation) and even lesser to change in CO_2 concentration – leading up to a maximum of just 46% increase under the 350ppm CO_2 emission level and 49% increase under the 700ppm CO_2 emission scenario.

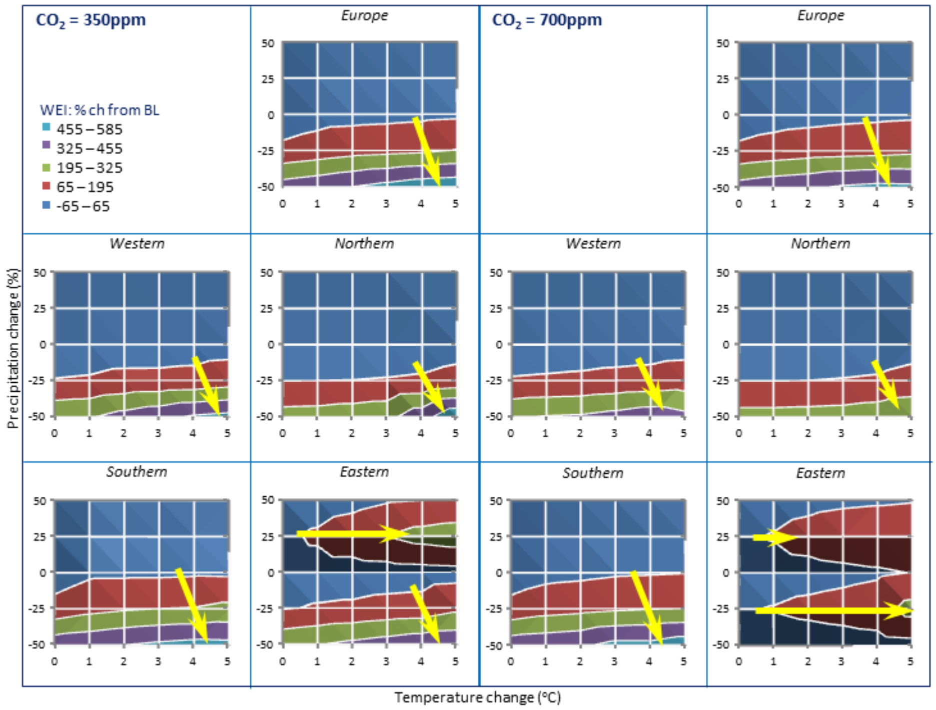


Figure 6.9: *Sensitivity of the % change in water exploitation index due to changes in temperature versus precipitation under baseline and future emission scenarios. Arrows show increasing trends (direction) and % change ranges (length).*

When looking at the regional sensitivities in terms of the relative change in WEI from their baseline values under the 350ppm CO_2 emission level, the highest regional increase in water stress is estimated in northern Europe with up to 566% increase in WEI under the hot-and-dry scenario (i.e., with a 5^{o}C temperature increase and 50% decline in precipitation from baseline), followed by southern and western Europe (with about 498% increase in WEI). In contrast, the highest reduction in water stress is estimated in southern Europe with up to 59% decline from baseline (under a scenario with Temp=5^{o}C and Prec=+50%), followed by western and northern Europe with about 46% decline from baseline. Under the 700ppm CO_2 emission scenario, the highest sensitivity in WEI is projected in southern Europe: declining by up to 52% and increasing by up to 536% from baseline. This is followed by western Europe with the sensitivity range between -47% and +408% from baseline. In relative terms, the least sensitivity of WEI to changes in climatic drivers is estimated in eastern Europe. A regional comparison of the results generally reflects the baseline conditions of the regions and the varied relative implications of future changes in temperature and precipitation levels, especially under the extreme scenarios.

Biodiversity vulnerability index

The biodiversity indicator, BVI, also shows a significant sensitivity to changes in the climatic drivers, especially temperature and precipitation changes. Vulnerability generally increases with increase in temperature (as well as with increasing CO_2 emission levels, albeit relatively small in magnitude) (i.e., a positive correlation) and decreases with increasing precipitation from baseline (i.e., a negative correlation) (Figure 6.10). In terms of the magnitudes of change, at the European scale BVI increases under most of the scenarios, increasing by up to 41% and 44% both under the extreme hot-and-dry scenario (i.e., with a 5°C increase in temperature and 50% decline in precipitation from the baseline) combined with the current (350ppm) and the highest future (700ppm) CO_2 emission levels, respectively. However, some scenarios lead to a small improvement in vulnerability, especially under the extreme wet scenarios (such as with a 50% increase in precipitation combined with baseline temperature setting) leading to a decline in BVI (improving vulnerability) by up to 13% and 4% from the baseline under the current and future CO_2 emission levels, respectively.

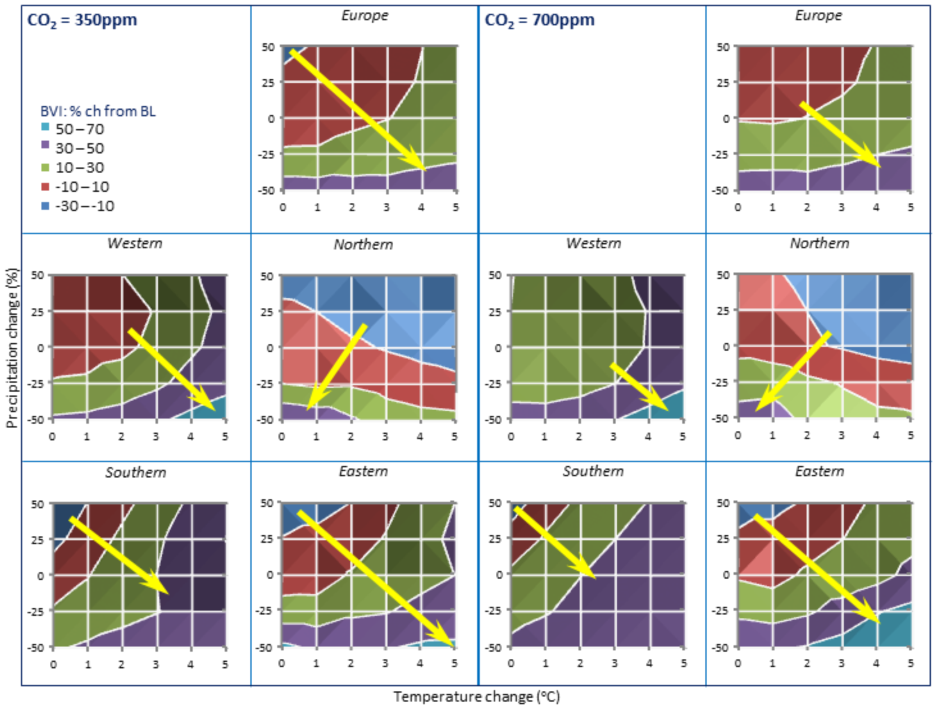


Figure 6.10: *Sensitivity of the % change in biodiversity vulnerability index due to changes in temperature versus precipitation under baseline and future emission scenarios. Arrows show increasing trends (direction) and % change ranges (length).*

When the regional sensitivities are considered, the highest increase in BVI under the 350ppm CO_2 emission level is estimated in western Europe (with a maximum of 61% increase from baseline under the extreme, hot-and-dry, scenario with Temp=+5°C and Prec=-50%), followed by eastern Europe (with a 55% increase associated with a 50% decline in precipitation under the baseline temperature) (Figure 6.10). In contrast, northern Europe (with a 28% decline in BVI under a scenario with Temp=+5°C and Prec=+25%) and southern Europe (with a 25% decline in BVI under a scenario with 50% increase in precipitation and no temperature change) are identified with the highest improvement in vulnerability from baseline. This is followed by eastern Europe with up to 20% decline in BVI from baseline under a scenario with 50%

increase in precipitation and baseline temperature. It is worth noting that, while an increase in temperature generally has a negative effect on biodiversity in all the three European regions leading to an increase in BVI, it has an opposite (positive) effect in northern Europe with a decline in vulnerability due to increasing temperature. This is mainly associated with a north ward shift of some species from the south as a result of a favourable climate space in the north under a warming climate scenario. In contrast in western Europe, although most of the climatic scenarios lead to a significant increase in BVI, there is some very small (less than 2%) improvement (decline in BVI) under a scenario with a 25% increase in precipitation combined with no temperature change). When the future CO_2 emission scenario is considered, both western and eastern Europe are identified as with the highest sensitivity with a 63% increase in BVI from the baseline, followed by southern and northern Europe with a 48% and 38% increase in BVI, respectively. In contrast, except western Europe, there is a significant improvement in vulnerability in the other three European regions with a decline in BVI ranging between 14% and 18% (in eastern and southern Europe, respectively, under a scenario with a 50% increase in precipitation combined with no temperature change) to a 25% decline in northern Europe under the extreme hot-and-dry scenario (i.e., with a 5^{o}C increase in temperature combined with a 50% increase in precipitation). In contrast, BVI change in western Europe shows increasing-only trend under all the climatic scenarios considered.

Focussing only on the sensitivity trends based on changes in the area-aggregated estimates hides a lot of sensitivities and uncertainties that takes place in the grid-based spatial impact distributions, particularity at the extremes. To address this, the study further extended the analysis to summarise the full statistical percentile distribution of the changes in indicators per grid as box-and-whisker plots focussing on the median and the 5th, 25th, 75th, and 95th percentile distributions of the indicators grid cell values for a total of 23,871 grids (Europe), as well as 7,166 grids (western), 4,532 (southern), 4,432 (eastern), and 7,741 (northern) Europe, as discussed in the following sections.

6.3.2 Distribution of the grid-based impacts at the European scale

Figure 6.11 presents the Europe-wide percentile distribution of the grid cell estimates of the indicators at the baseline (BL), and under the various climate scenarios grouped by different CO_2 emission levels as well as across the full ranges (i.e., ALL) of climate scenarios considered. Except for urban (where there are no changes in AS, as the climatic drivers do not have any effect), the results show significant variation in the distribution across the sectors/sub-systems and scenarios as discussed below in more detail.

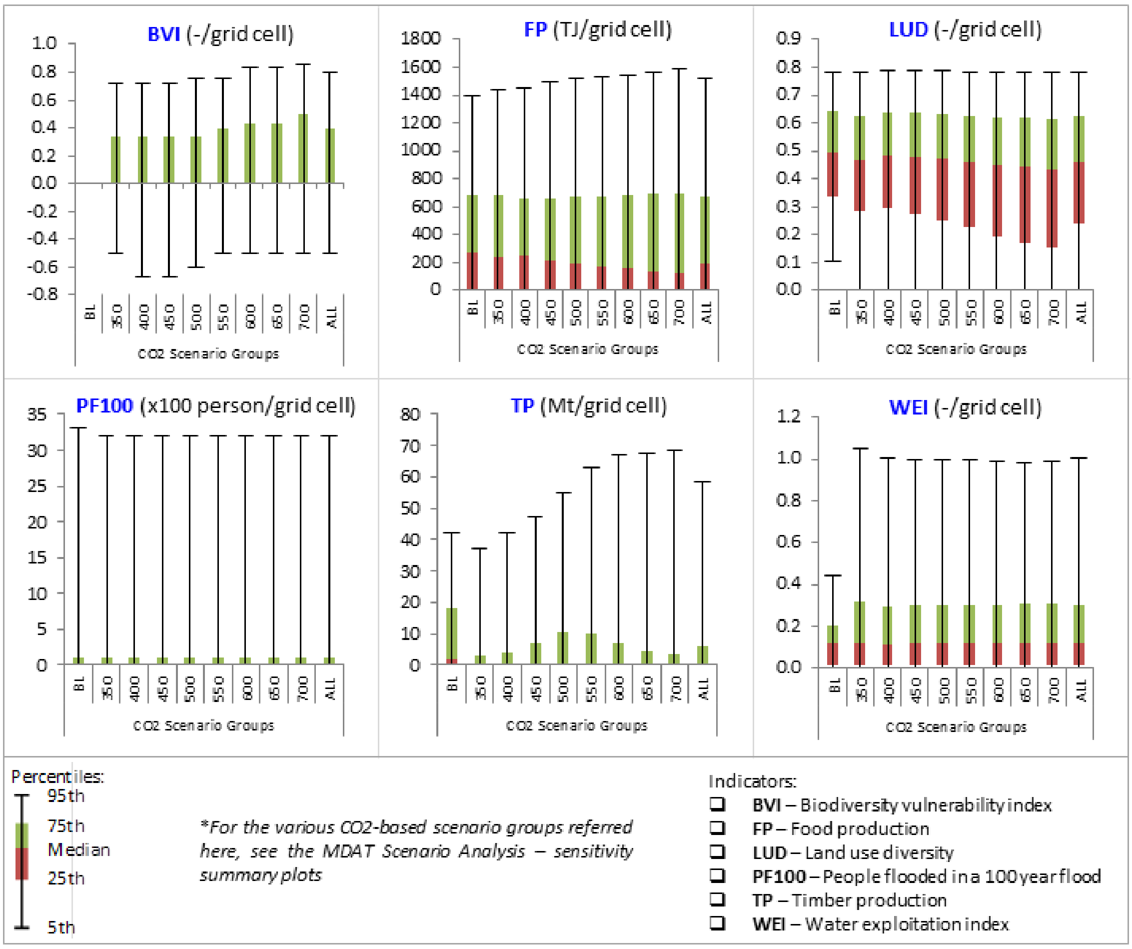


Figure 6.11: *European summary of the percentile distribution of indicators (per grid cell) at the baseline (BL) and across the various climate scenarios grouped by CO_2 emission levels.*

People flooded in a 1 in 100 year flood event (PF100)

At the European scale, the grid cell level estimates of PF100 mostly show very small changes; with the median value being zero and the 75th percentile value estimated 100 people across all the scenarios (Figure 6.11). However, the results show significant local changes in the extreme values as reflected by the 95th percentile value estimates changing from 3,300 people at the baseline to ranging between 2,800 and 3,600 people under some extreme scenarios (with an average estimate of 3,200 people across the scenarios). Areas with the highest impacts are found in regions with high population density within low-lying areas of the coastal and fluvial floodplains.

Land use-related indicators: food production (FP), timber production (TP) and land use diversity (LUD)

For FP, the 25th percentile grid cell value estimate is zero both at the baseline and under the various scenarios, indicating that at least 25% of the grid cells across Europe represent non-agricultural land (e.g., urban areas or floodplains that are not suitable for agriculture due to frequent flooding). Whilst the 75th percentile grid cell values show only small changes from the baseline (with the highest decline estimated at 4.5% under CO_2=400ppm emission), there are diverging trends in terms of the median and the 95th percentile grid cell values under the scenarios grouped by increasing CO_2 estimates. Also, the median value decreases by up to 56% (from baseline), while the 95th percentile grid cell values are projected to increase by up to 14%, both under the CO_2=700ppm emission scenario. These divergent trends also reflect the spatial patterns of FP across Europe where there is a significant decrease in at least 50% of the grid cells (e.g., in southern Europe) that is compensated by an increase especially at the extremes (e.g., some grid cells in northern Europe) to maintain the European level FP under the various scenarios.

For TP, there is a decline in most grid cells across Europe with zero median values under all the scenarios, reflecting at least 50% of the grid cells have no TP (either covered with other land use at baseline or completely lost their forest area (from baseline) to other land uses, mainly to agriculture). However, there is a significant variation in the extremes of the distribution: the 75th percentile decreasing by up to 83% (under the low CO_2 emission scenario) while the 95th percentile increasing by over 62% (under the highest CO_2 emission scenario) (Figure 6.11). When looking at the 75th percentile distributions, while there is less timber under most scenarios than at the baseline, the least percentage decline for 75% of the grid cells is estimated under the CO_2=500ppm emission with 42% decrease in grid cell values from baseline. On the other hand, the extreme distribution of the 95th percentile grid cell values increases from baseline values with increasing CO_2, with the highest extreme grid cell values reaching up to 70Mt timber, reflecting that there is improvement in timber production in some areas under the higher CO_2 emission scenarios.

The European scale LUD also shows some variations with a shifting distribution, where the 25th percentile coverage decreasing from 0.35 (baseline) to 0.15 under CO_2=700ppm, while showing small or no change in terms of the higher percentiles reflecting unchanged diversity across Europe.

Water exploitation index (WEI)

For WEI, the results show that although there is only a small/no change in terms of the median values, the grid cell values show significant increase from baseline in terms of the extreme distributions across all the scenarios. For example, the 75th percentile increases by up to 54% (i.e., from 0.2 at baseline to 0.3 under the CO_2=350ppm emission level), and the 95th percentile coverage increases from 0.45 (baseline) to 1.05 under current emission level (i.e., a 135%

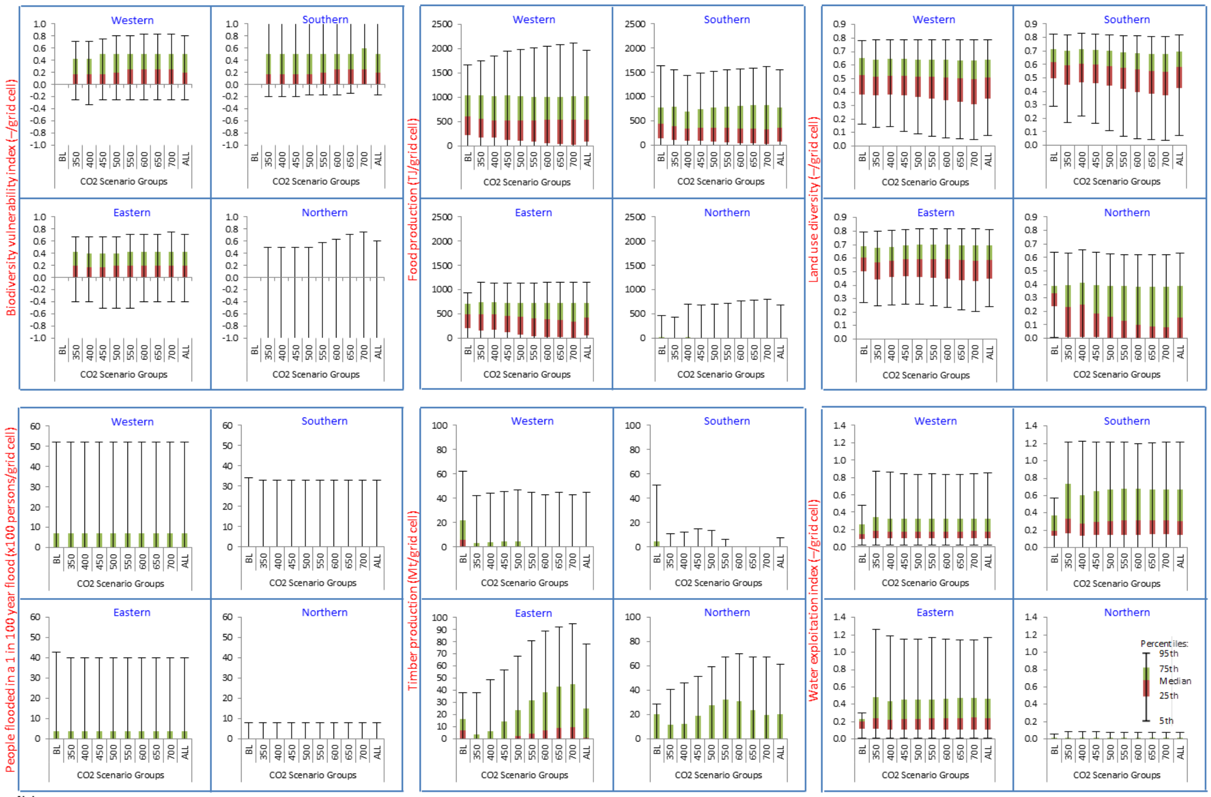
increase, reflecting a significant increase in water stress across Europe except in some places representing only 5% of the distribution).

Biodiversity vulnerability index (BVI)

For the Europe-wide BVI, both the median and the 25th percentile are both zero, indicating that at least 25% of the grid cells show no change (from baseline) across all the scenarios. In contrast, there is a significant improvement (reduction) in BVI in terms of the 5th percentile (with BVI < -0.5, mainly in northern Europe), while the 75th and 95th percentile estimates generally show a significant increase in BVI across the scenarios, ranging between 0.3 and 05 (75th percentile) and 0.7 and 0.9 (95th percentile). These estimates generally reflect that more than 30% of the species will no longer have appropriate climate/habitat space in at least 75% of the grid cells across Europe under the various climate scenarios (Figure 6.11).

6.3.3 Distribution of the grid-based impacts at the regional scale

Figure 6.12 presents the regional level percentile distributions of the indicators at the baseline (BL), under the various climate scenarios grouped by CO_2 emission levels, and across the full ranges ('ALL') of the climate scenarios. The results show significant variation in distribution across the regions and sectors/sub-systems as discussed below.



Note:

- For comparison, the same scale in the y-axes is used for each indicator across the four European regions
- BL – Baseline
- ALL – All the climate scenarios considered
- For the various CO2 Scenarios Groups referred here, see the MDAT Scenario Analysis sensitivity summary plots

Figure 6.12: *Regional summary of the percentile distribution of indicators (per grid cell) at the baseline and across the various climate scenarios grouped by CO_2 emission levels.*

People flooded in a 1 in 100 year flood event

Although there are significant regional variations at the extreme distributions, both the median and the 25th percentile coverage of PF100 are both zero under all the scenarios in all regions (Figure 6.12). This reflects that up to 50% of the grid cells in each region (particularly in western and eastern Europe) are either outside the (coastal or fluvial) floodplains or are in areas that are protected by flood defences (with a 100 year or more standard of protection). The 75th percentile is also zero in southern and northern Europe, indicating that only 25% of the grid cells in the regions are at risk of flooding due to a 100 year flood event. The results also indicate that flood impacts are significant locally, as reflected by the extreme percentile distributions. While there are only small/no variations across the scenarios, the 95th percentile is estimated highest in western Europe with grid cell values reaching up to 5,200 people flooded, followed by in eastern and southern Europe with grid cell values of 4,000 and 3,300 people flooded, respectively, under the various climate scenarios.

Land use-related indicators: food production, timber production and land use diversity

Except in northern Europe, there is a significant variation in the spatial distribution of FP per grid across the regions, with only up to 5% of the grid cells in each region representing non-agricultural land (e.g., urban areas) across all the various scenarios (Figure 6.12). In western Europe, both the median and 75th percentile values show a small/no change, with the highest estimated at -2.5% (under CO_2=600ppm) and -14% (under CO_2=400ppm) change from baseline, respectively. However, there is a significant declining trend in the 25th percentile distribution across the scenarios (i.e., with the grid cell values decreasing from 230TJ (baseline) to just 32TJ/grid under the CO_2=700ppm emission scenario, which is an 85% decrease). In contrast, the 95th percentile grid cell values increase by over 26% from 1,678TJ (baseline) to 2,121TJ under the CO_2=700ppm emission scenario. These estimates reflect the varying trend in the distribution indicating the expansion of FP in the region under the scenarios with increasing CO_2 concentration. In contrast, in southern Europe all the percentile distributions under the scenarios generally show a decline in grid cell values from the baseline, which also reflects the overall decrease in FP in the region under most of the scenarios, particularly under the low CO_2 emission scenarios. In northern Europe, while there are modest changes in FP locally as reflected by the extremes, at least 75% of the grid cells have no change.

For TP, the highest variation in the spatial distribution of the grid cell estimates is in eastern Europe with a significant increase in the percentiles from baseline, particularly at the extreme distributions, associated with increasing CO_2 across the scenarios (Figure 6.12). For example, both the 75th and 95th percentile coverages increase from baseline, particularly under scenarios with more than 450ppm CO_2; each increasing by up to 178% (i.e., from 16Mt/grid to 45Mt/grid) and 150% (i.e., from 38Mt/grid to 95Mt/grid), respectively, under the CO_2=700ppm emission scenario. In northern Europe, although up to 50% of the grid cells show zero TP in the regions, there is however a similar pattern in terms of the extreme distributions, with both the 75th and 95th percentiles increasing from baseline by up to 61% and 143%, respectively, under the CO_2 between 550ppm and 600ppm levels. In contrast, in southern and western Europe, although there are small changes in the distribution across the scenarios, there is a significant decline in TP from baseline.

The LUD shows changes in the various land uses in each region. Although the high extreme percentile distributions are almost unchanged from baseline (with the 95th percentile value of 0.8 in all regions, except northern Europe with 0.6) under the various scenarios, there is a significant decline in the 5th and 25th percentile coverages, particularly in western and southern as well as northern Europe, reflecting a locally significant decline in LUD. This is associated with, for example, the expansion of one land use (e.g., agriculture/forest) at the expense of other land uses. The highest variation is in southern Europe, with the 5th percentile decreasing from 0.29 (baseline) to 0.04 under the CO_2=700ppm scenario.

Water exploitation index

Although there are only very small variations in the distributions under the various scenarios, the grid cell WEI values increase significantly under the future scenarios when compared with the baseline distribution in all regions (Figure 6.12). The highest increases are estimated in southern and eastern Europe. The 95th percentile grid cell values in the two regions increases on average (across the various scenarios) by up to 120% (from 0.6 (baseline) to 1.4 under CO_2=350ppm) and 292% (from 0.3 (baseline) to 1.3 under CO_2=350ppm), respectively, indicating a significant localised WEI increase in the regions. In contrast, in western Europe the 95th percentile coverage increases from 0.5 (baseline) to 0.9 under the CO_2=350ppm emission. However, in northern Europe the changes are very small relative to other regions, with the highest percentile estimated below 0.2, indicating the relatively low water stress related issues in the region.

Biodiversity vulnerability index

The regional estimates also show that there are some improvements in BVI, as reflected by the negative values of the 5th percentile distribution across all the regions (Figure 6.12). The highest improvement is projected in northern Europe, with about 5% of the grid cells in the region having suitable climate/habitat space for all the species. In contrast, the zero median and 25^{th} and 75^{th} percentiles indicate that at least 25% of the grids have no change in the total number of species that are vulnerable. However, BVI in the other regions (south/west/east) increases significantly under the various scenarios. For example, the 75% grid cell coverages are estimated with BVI=0.5, indicating that up to 50% of the species in each region no longer have appropriate climate/habitat space.

6.4 Sensitivity of Cross-Sectoral Impacts due to Socio-Economic Change Scenarios

This section presents (i) a sensitivity analysis of the trends in future changes of the area-aggregate cross-sectoral impacts at the European and regional scale (Section 6.4.1), (ii) the percentile distribution of the grid-based changes in the indicators across Europe and the four catchment-based regions (Section 6.4.2) under the full ranges of socio-economic scenarios.

6.4.1 Area-aggregate impact sensitivity trends at European and regional scales

Figure 6.13 presents the effect of individual drivers and the aggregated summary of the sensitivity trends of the sectoral indicators under the various socio-economic scenario combinations grouped based on changes in population (between -50% and +50% at every 25% increase from baseline) and GDP (at GDP=-20% (from baseline) and between 0 and 200% at intervals of 50% increase from baseline). Unlike the effect of the climatic scenarios, most sectors/sub-systems in all regions are sensitive to most of the socio-economic scenarios considered, with varying degree of change in indicators from the baseline. In addition, most sectors/sub-systems on aggregate show robust directions of change, including an increase-only trend in AS and BVI as well as a decline-only trend in TP. LUD also shows a decline-only trend both at the European and regional scales (except in western Europe with a small increase of up to 3% from baseline). The highest regional sensitivity range in LUD is estimated in northern Europe at 43%, which is mainly associated with the significant expansion of agricultural land in the region under most scenarios: this either leads to a growing demand in food (e.g., due to growing population) or increased productivity. Other sectoral indicators show both increase and decrease from baseline under the various socio-economic scenarios depending on the magnitudes of change in the drivers. However, when the magnitudes of change in the indicators are considered, in comparison AS followed by BVI and LUD indicators are identified as least sensitive to changes in the socio-economic drivers. The highest sensitivity ranges in terms of the % change from baseline across the five regions are estimated between +0.4 and

6.8% (AS), +1.2% and 31.5% (BVI), and -43% and 3% (LUD) change from baseline. In contrast, FP, PF100 and WEI are all identified with the highest sensitivity range to changes in the socio-economic drivers. Under the extreme scenarios, the highest sensitivity ranges are estimated between -77% and 103% (FP), between -50% and +129% (PF100), and between -17% and +158 (WEI) change from baseline.

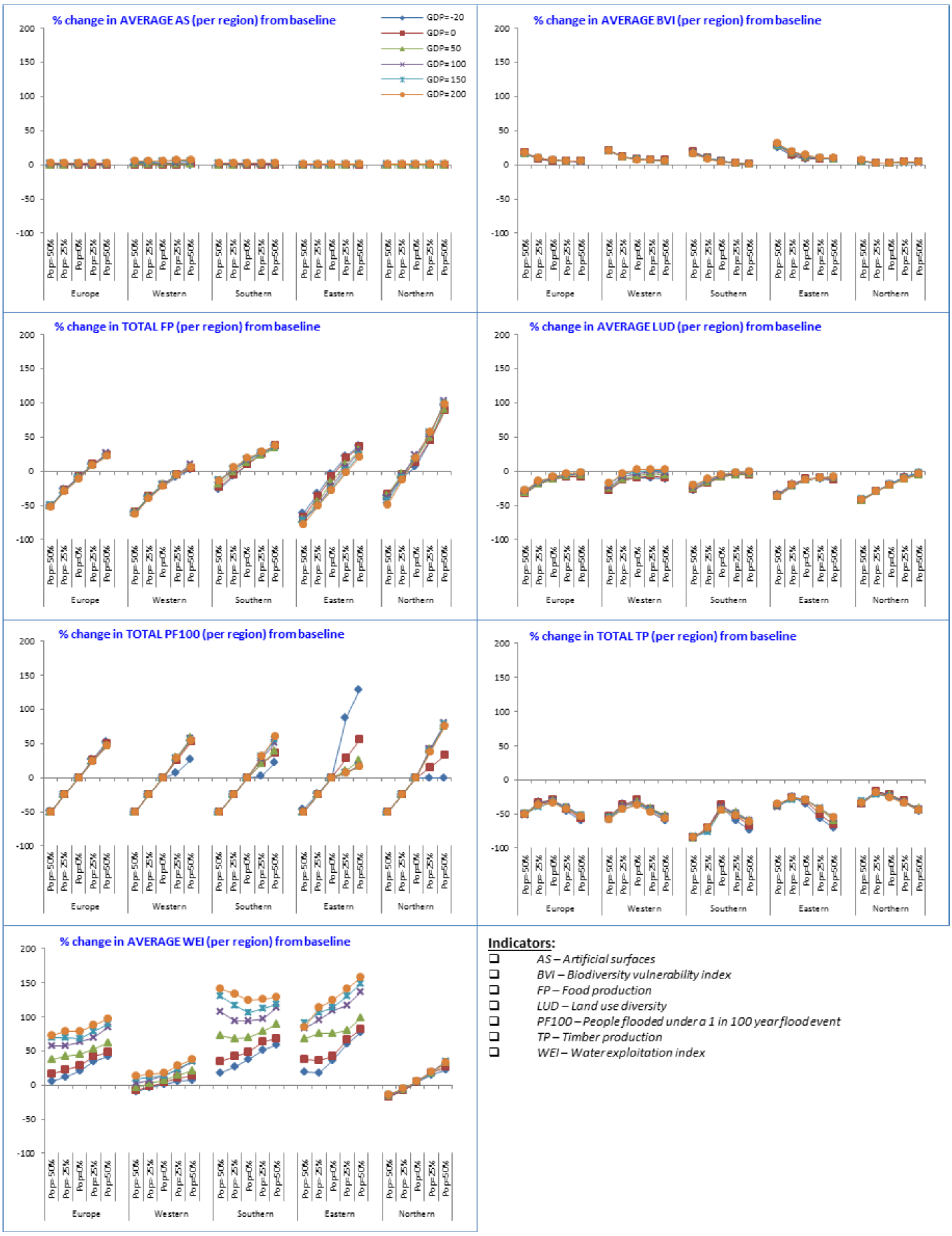


Figure 6.13: *Sensitivity of impacts based on the % change in indicators (from baseline) for Europe and the four regions under the 'full' ranges of socio-economic change MDAT scenarios grouped by*

change in population and GDP. NB: Each data point represents an ensemble mean % change of 20 scenarios of combined change in food imports and agricultural yield. See Figures 6.14–6.20.

In terms of the cross-sectoral comparison, at the European scale the highest changes in the indicators from baseline are estimated at a 96% increase in WEI (under a scenario of wealthiest and highest projected European population). This is followed by a 52% increase in PF100 (under a scenario with the highest population projection combined with a declining GDP). The highest decline in TP, FP and PF100 are estimated at 60% (under Pop=+50% and GDP=-20%), 53% (under Pop=-50% and GDP=+200%), and 50% (under a scenario with a 50% increase in population, regardless of the change in GDP), respectively. In contrast, BVI shows increasing-only trend from baseline across all regions (including northern) under all the scenarios, with the highest and lowest sensitivity estimated in eastern and northern with a range of 31% and 7%, respectively.

In western Europe, PF100 is identified as the highest sensitive indicator to changes in the socio-economic drivers (especially population change) with a sensitivity range estimated at 109% (ranging between -50% and +59% change from baseline), followed by FP with a sensitivity range of 74% (-63% and +10%) and TP with a sensitivity range 60% (-60% and -30% showing a decline-only trend across all the scenarios). As in the European case, AS shows the least overall sensitivity to changes in the socio-economic drivers with just 7% increase from baseline, mainly due to change in GDP. However, in comparison with other regions this is the highest regional urban change in Europe – other regions estimated below 4% increase in AS; eastern Europe being the least. In contrast, PF100 and WEI in western Europe are estimated with the least sensitivity range in comparison with other regions. However, in southern Europe, both WEI and PF100 are estimated with the highest sensitivity than all other sectors/sub-systems with sensitivity range of 140% (between +18% and +140%, showing increasing-only trend from baseline) and 110% (between -50% and +60% change from baseline), respectively. This is followed by TP and FP with a sensitivity range of 85% (with a decline-only trend from baseline and the highest regional decline in TP when compared with other regions) and 64% (between -26% and +38% change), respectively.

In contrast, most sectors/sub-systems experience significant impact/change in eastern Europe with the highest sensitivity to changes in the socio-economic drivers, when compared to other regions. Again PF100 and WEI are estimated with the highest sensitivity range than all other sectors/sub-systems, with a 179% (between a 50% decline and a 129% increase) and 158% (between +18% and +158%, also showing increasing-only trend as in southern Europe) from the baseline. These estimates are also the highest regional sensitivities for each sector/sub-system when compared with other regions. In addition, the highest regional change in BVI is also estimated in eastern Europe with a total sensitivity range of 31% change from baseline (with an increase-only trend). Furthermore, in terms of the regional comparisons, FP and TP in eastern Europe are also the second highest (next to northern for FP and southern for TP) sensitivity range of changes from baseline estimated at 115% (between -77% and +38%) and 70% (with a decline-only trend), respectively.

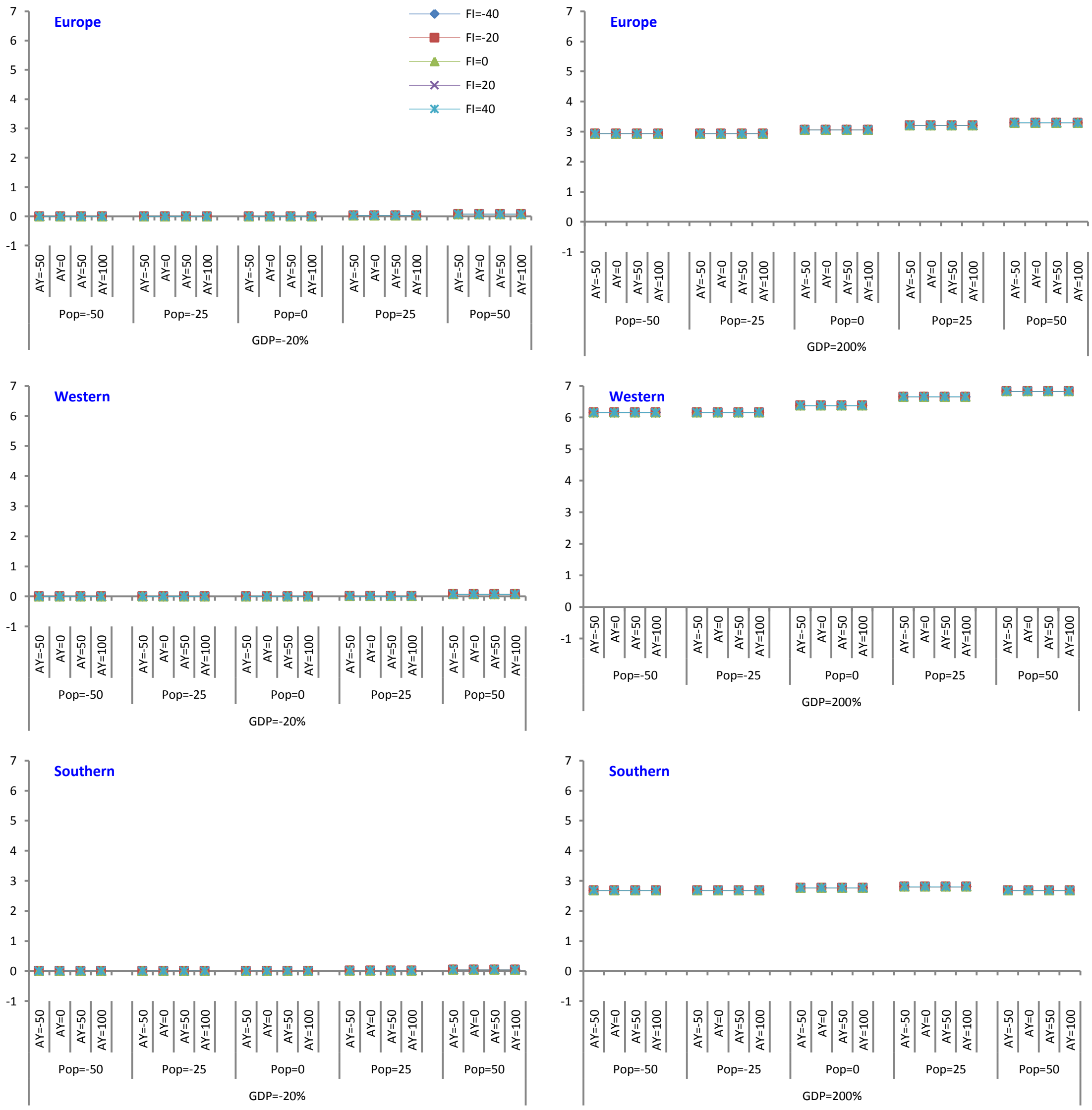
In northern Europe, FP has by far the highest change than all other sectors/sub-systems, with a sensitivity range estimated between a 48% decline and a 103% increase from baseline. These extreme changes are mainly driven by change in population; for example the highest increase in FP being due to the need to meet the increasing food demand under the scenario with a 50% population and 100% GDP increase from baseline. PF100 follows with a 131% sensitivity range between a 50% decline (due to a 50% decrease in population – also illustrating a positive and linear correlation) and 81% increase (under a 50% population and 100% GDP increase) from baseline. WEI also shows a significant sensitivity (with a range estimated at 52%, i.e., between a 17% decline under the extreme scenario with a 50% and 20% decline in population and GDP, respectively). TP and LUD follow with a sensitivity range estimated at 46% and 43%, respectively, and both with a decline-only trend from baseline under all scenarios.

The following sub-sections present a more detailed discussion of the changes in each sectoral indicator under the various scenario combinations of change in the four key socio-economic drivers (i.e., *food imports*, *agricultural yields*, *population*, and *GDP*). The figures included below (Figures 6.14–6.20) present the summary of the sensitivity trends at the Europe scale and the four regions and across the various scenario combinations.

Artificial surfaces

As discussed in Section 6.3, the climatic drivers have no effect on urban change. The main drivers of change in AS are GDP change followed by population change – both with a positive correlation with AS. However, the effects of both drivers are relatively marginal when compared with the sensitivities of other sectors/sub-systems to these and other climatic and socio-economic drivers. Figure 6.14 presents the sensitivities of AS to changes in four socio-economic drivers. The results show that AS is insensitive to changes in both agricultural yields and food imports. However, there are small changes in AS associated with the changes in GDP and population – with an increasing-only trend from baseline under all the scenarios considered in all regions, GDP being the dominant driver of urban change.

For example at the European scale, AS increases by up to 3.3% from the baseline under the extreme socio-economic scenario with a 200% GDP and 50% population increase from the baseline. This is mainly driven by GDP change, while only 7% of the increase is associated with population change. When considering the regional projections, the highest sensitivities are estimated in western Europe with up to a 7% increase in AS from the baseline, followed by a 3% increase in southern Europe under the scenario with GDP=+200% and Pop=+50% change from baseline. In contrast, a very small sensitivity is observed in both northern and eastern Europe with just 0.6% and 0.4% change in AS, respectively, across all the scenarios.



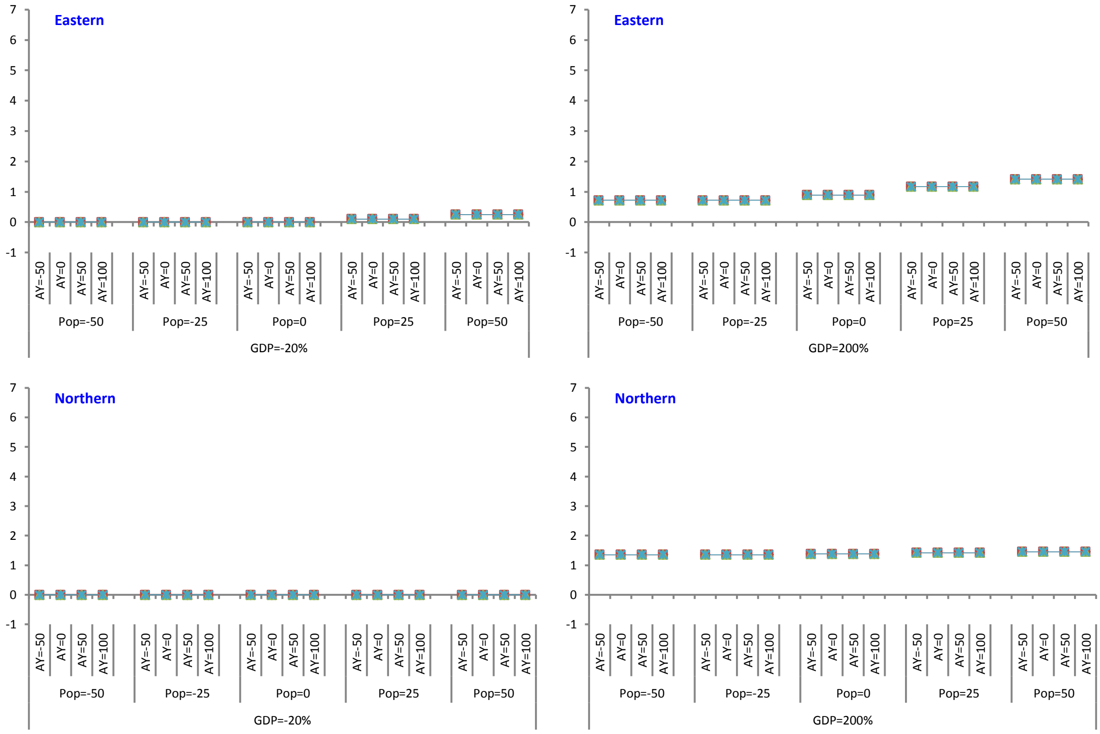


Figure 6.14: *Sensitivity of the % change of the regional average artificial surfaces from baseline under various socio-economic scenarios.*

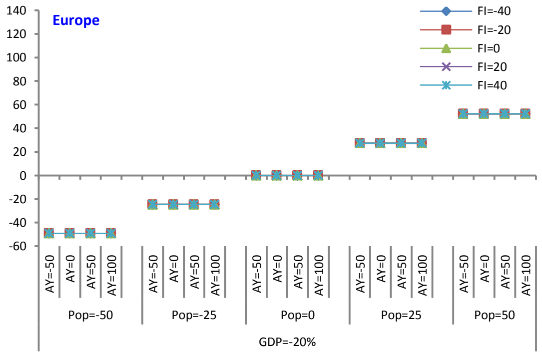
People flooded in a 1 in 100 year flood event

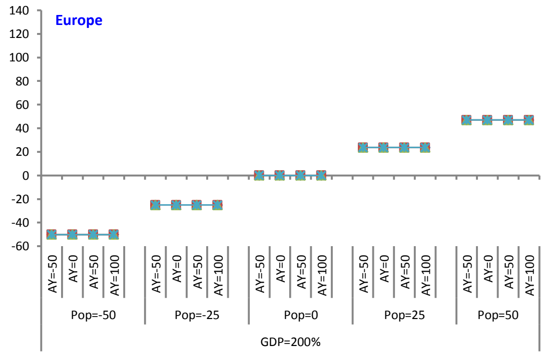
Figure 6.15 presents sensitivities of PF100 to changes in the four socio-economic drivers. The results show that PF100 is highly sensitive (directly/indirectly) to population change and marginally (particularly at the European scale) sensitive to GDP change (indirectly through urban change when combined with population change). However, it is totally insensitive to the other two drivers: agricultural yields and food imports. There is a positive correlation between PF100 and population change in all regions – PF100 increasing with increase in population. In contrast, although GDP has no effect on PF100 independently, when combined with population change it has varied implications (or correlation) across the different regions under the various scenarios, due to the indirect effects through changes in AS.

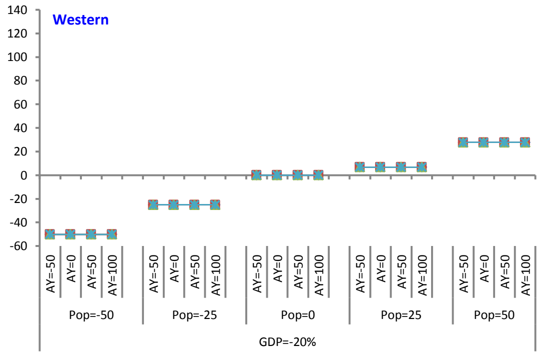
At the European scale, the sensitivity of PF100 is estimated between a 50% decline and a 52% increase under the extreme scenarios of -50% and +50% changes in population, respectively. Although relatively small in magnitude, GDP change (when combined with population change) has opposite effect on number of people flooded. For example, when considering a 50% increase in population, PF100 increases from 17.4 million people at the baseline to 25.7 million people due to population change alone (i.e., the 50% increase) only; but it further increases to 26.3 million people (when combined with a 20% decline in GDP, which is equivalent to a +3% contribution due to GDP change (decline) alone) and 25.3 million people (when combined with a 200% increase in GDP – which is about a -5% contribution due to GDP change (increase) alone).

When regional sensitivities are considered, as in the European level estimates, the effect of population change is in comparison more pronounced than that of GDP change (Figure 6.15). In contrast, eastern followed by northern Europe show the highest sensitivity under the extreme scenarios: with ranges estimated at up to 179% (between a 50% decline under Pop=-50% combined with no/+ve GDP change and a 129% increase in PF100 under a scenario with Pop=+50% and GDP=-20%) for eastern Europe and 131% (between a 50% decline under Pop=-50% and an 81% increase under Pop=+50% combined with GDP=+100% scenario) for northern Europe. There is also a significant change in PF100 from baseline in both western and southern Europe – with sensitivity ranges estimated at up to 110% under the extreme scenarios.

Furthermore, the effect of GDP (when combined with population change) is particularly significant in eastern Europe when compared with other regions. PF100 generally shows a negative correlation with GDP, which decrease with increasing GDP combined with growing population. However, GDP change has very little/no effect on PF100 under scenarios with declining population. For example, under the extreme scenario of a 50% increase in population, PF100 increases by up to 17% from baseline under a 200% GDP growth, while increasing by up to 129% from baseline under a 20% decline in GDP from the baseline. However, in southern Europe, the effect of GDP shows a positive correlation with PF100 – where increasing GDP leads to increase in PF100 under scenarios with growing population. For instance, PF100 in southern Europe is estimated at 3.4 million people at the baseline and considering a scenario with a 50% increase in population PF100 increases from 4.6 million people with no change in GDP (i.e., a 36% increase from baseline, which is due to population change alone) to 5.4 million people (i.e., a 60% increase from baseline) under a 200% growth in GDP (which is about 24% increase due to GDP change alone). However, in northern and western Europe, there are no clear trends in PF100 changes due to change in GDP – with the highest impacts estimated at 81% increase in PF100 in northern Europe due to a 100% GDP growth and a 59% increase in PF100 in western Europe due to a 50% growth in GDP.


Europe
FI=-40
FI=-20
FI=0
FI=20
FI=40
Pop=-50
Pop=-25
Pop=0
Pop=25
Pop=50
GDP=-20%


Europe
Pop=-50
Pop=-25
Pop=0
Pop=25
Pop=50
GDP=200%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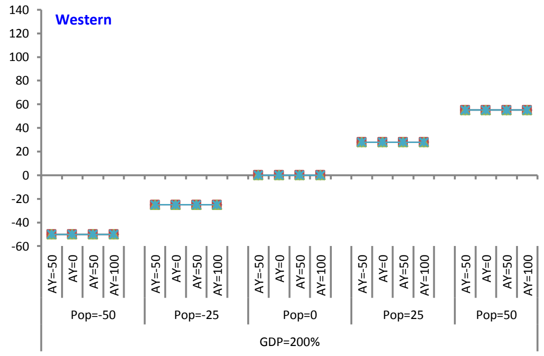
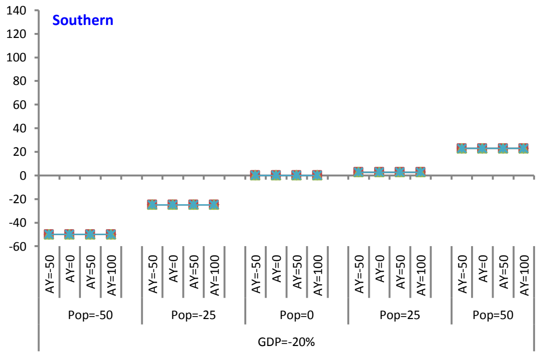
Pop=-50
Pop=-25
Pop=0
Pop=25
Pop=50
GDP=-20%


Western
Pop=-50
Pop=-25
Pop=0
Pop=25
Pop=50
GDP=200%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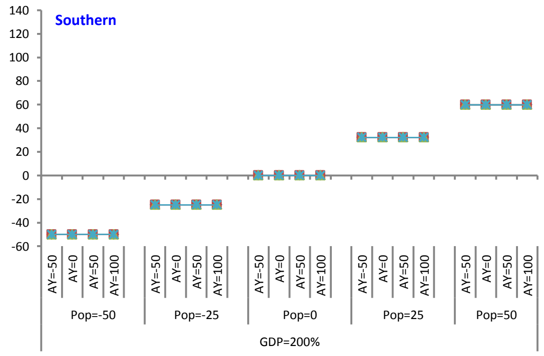
Pop=-25
Pop=0
Pop=25
Pop=50
GDP=-20%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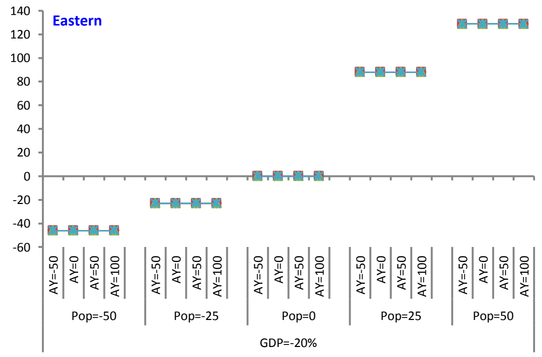
Pop=-25
Pop=0
Pop=25
Pop=50
GDP=200%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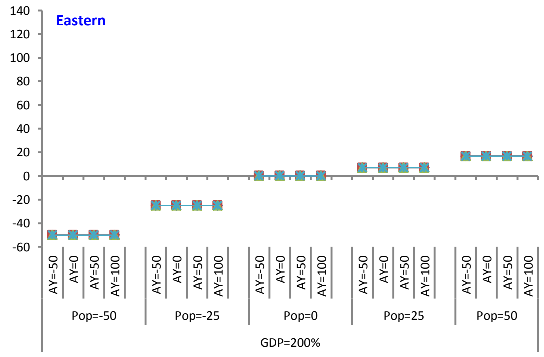
Pop=0
Pop=25
Pop=50
GDP=-20%


Eastern
Pop=-50
Pop=-25
Pop=0
Pop=25
Pop=50
GDP=200%

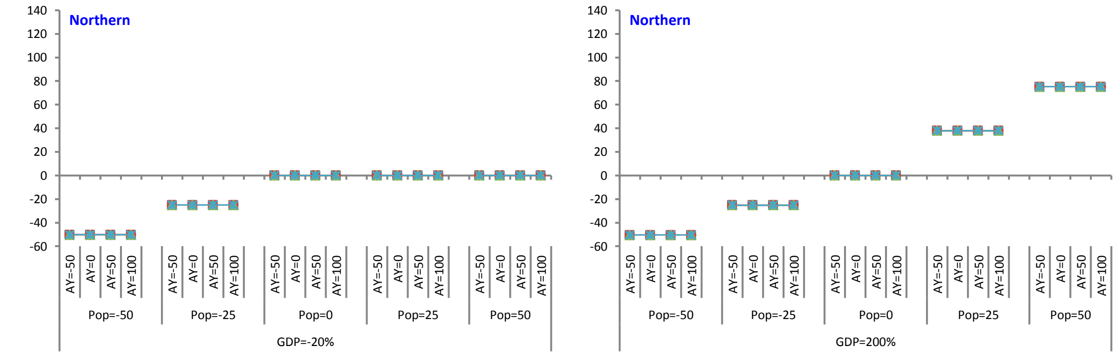


Figure 6.15: *Sensitivity of the % change of the regional total number of people flooded from baseline under various socio-economic scenarios.*

Land use related indicators: food production, timber production and land use diversity

Figure 6.16 presents a summary of the sensitivity of FP to combined changes in population, GDP, food imports, and agricultural yields under various scenario combinations. The results show that FP is sensitive to all of the four drivers resulting in complex interactions with both direct and indirect implications on future FP across Europe. At the European scale, FP generally shows a positive correlation with change in population as well as agricultural yields (FP increasing with increasing population and yields). In contrast, it has a negative correlation with change in food imports (FP decreasing with increasing imports). However, although with an overall declining trend between extreme scenarios, there is less clear relationship with GDP change due to its indirect implications. This is mainly associated with changes in demand and availability of water for irrigation, which have complex interacting effect on FP resulting in projections both increasing and decreasing from baseline under the various scenarios.

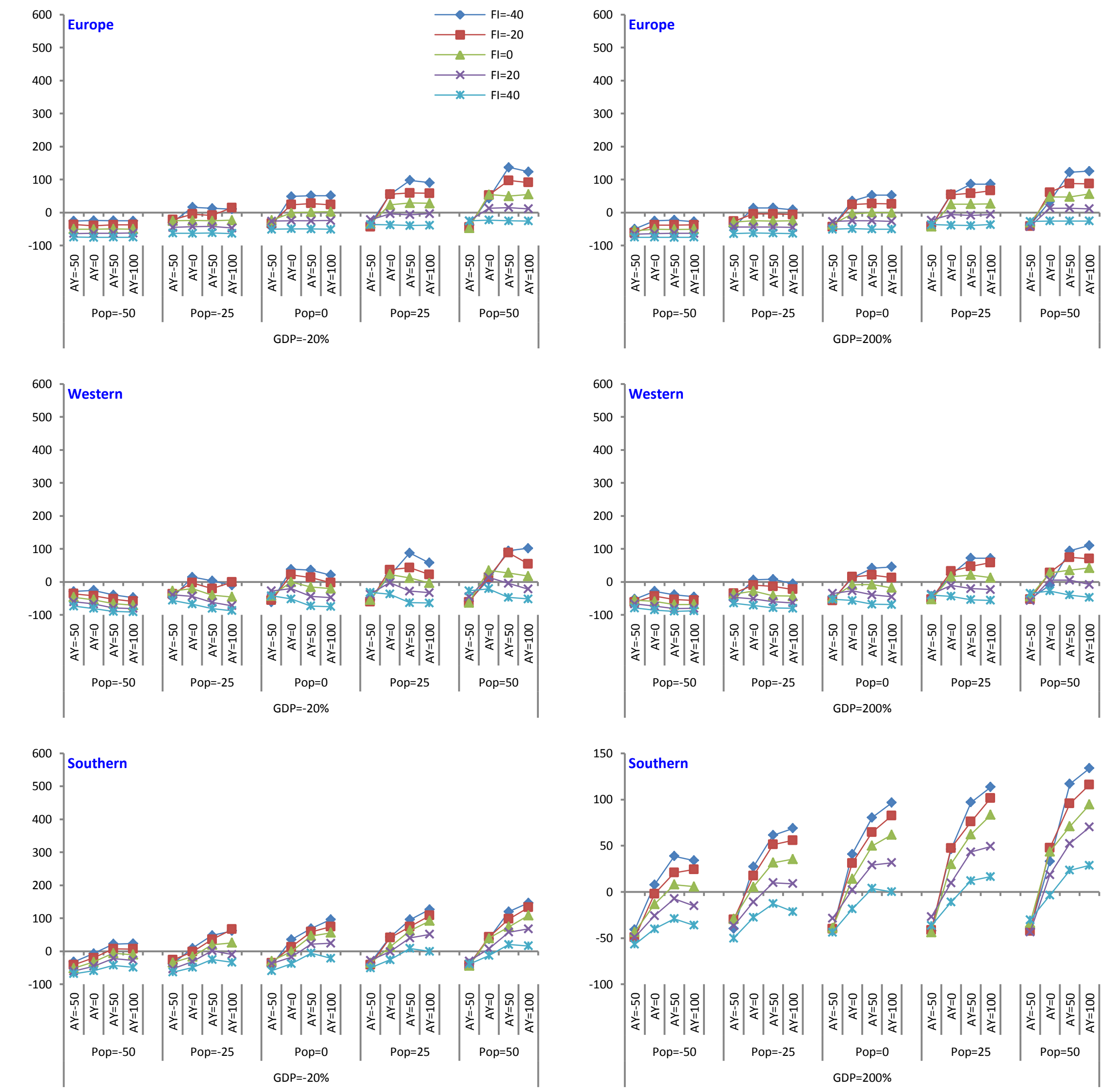
In terms of the relative (from baseline) magnitude of change in Europe-wide FP, the overall sensitivity range is estimated at 213% – changing between a 76% decline (under a scenario with GDP=+100%, Pop=-50%, AY=+50%, FI=+40%) and a 137% increase (under a scenario with GDP=-20%, Pop=+50%, AY=+50%, FI=-40%) in FP from baseline. The results show that changes in population and food imports are the two dominant drivers of change in future food demand and supply, respectively. However, these projections also demonstrate that despite the nature of the individual driver-indicator relationships (positive/negative correlation), the overall change in FP is a result of the complex interactions and associated cumulative (direct/indirect) effects of the various drivers. For example, under the high extreme scenario (which led to a 137% increase in FP), the effect of the individual drivers (keeping other drivers constant) is estimated at: (i) a 52% increase due to a 50% population growth, (ii) a 49% increase due to a 40% decline in food imports, (iii) a 1% decline due to a 20% decline in GDP, and (iv) a 1% decline due to a 50% increase in agricultural yields – with a total of 99% (i.e., 50% + 49% - 1% -

1%) overall increase in FP, when a simple sum of the effects of the individual drivers is considered. However, this is significantly different from the 137% food production increase estimated under the combined effect of the four drivers changing simultaneously, highlighting the complex interactions and associated cross-sectoral indirect implications of the drivers under the various scenarios. In addition, the results show that the overall sensitivities of FP to future socio-economic scenarios (including the effects of other drivers such as food imports) are generally more pronounced and show divergence at higher population increase scenarios than those scenarios with declining future population. Such implications also highlight the need for a better understanding of these interactions and the benefits of such comprehensive analysis to identify the key drivers and scenario combinations which can lead to significant implications in future food security issues in Europe.

When considering the regional sensitivities, as in the case at the European level, the regional FP also shows a clear positive correlation with change in population (FP increasing with growing population) and vice versa with food imports in all regions. In contrast, the regional implications of GDP change are varied – with growing GDP leading to an overall declining trend in FP in eastern and northern Europe, while leading to an overall increasing trend in western and southern Europe (although with a reduced rate at higher GDP scenarios) (Figure 6.16). However, there is significant regional variation in terms of the effect of changing agricultural yields on FP across the regions. In southern Europe, there is an 'almost-linear' and positive correlation between the regional FP and agricultural yields (ranging between a 24% decline and 55% increase in FP due to a -50% and +100 change in agricultural yields, respectively), while having a relatively non-linear and negative correlation in northern Europe with a 149% increase and 14% decrease due to a -50% and +100 change in yields, respectively), keeping all other factors constant. In contrast, in western and eastern Europe FP decreases with both increasing and decreasing agricultural yields, with a 34% and 19% (western) and 19% and 11% (eastern) decline in under a 50% decline and 100% increase in yields, respectively.

In terms of the relative magnitudes of change from baseline due to the effect of all the socio-economic drivers considered also varies significantly across the regions (Figure 6.16). The highest regional sensitivity in FP is projected in northern Europe with a significant sensitivity range of 601% change (from baseline) when compared with other regions – varying between an 82% decline (under a scenario with GDP=+200%, Pop=-50%, AY=+50%, FI=+40%) and a 519% increase (under a scenario with GDP=-20%, Pop=+50%, AY=+50%, FI=-40%) from baseline. Except for the change in GDP under the first scenario, the above two extreme scenarios also derive the overall Europe-wide extreme sensitivities – highlighting that the importance of potential future expansion and shift in agriculture-led land-use change towards northern Europe to meet the overall growing demand for food at the European scale.

In contrast, the sensitivity range in eastern Europe is estimated at 275%, i.e., between -97% and +178% change in FP from baseline (under the scenarios with GDP=200%, Pop=-50%, AY=+50%, FI=+40% and with GDP=-20%, Pop=+50%, AY=+100%, FI=-40%, respectively). This is followed by southern and western Europe with sensitivity ranges of 215%, i.e., between -68% and +146% under two extreme scenario combinations of GDP=-20%, Pop=-50%, AY=-50%, FI=+40% and GDP=-20%, Pop=+50%, AY=+100%, FI=-40%, respectively. While the least sensitivity is estimated in western Europe, with a range 201% (i.e., between a 91% decline and a 111% increase from baseline under the extreme scenario (with GDP=-20%, Pop=-50%, AY=+100%, FI=+40%) and (with GDP=+200%, Pop=+50%, AY=+100%, FI=-40%), respectively.



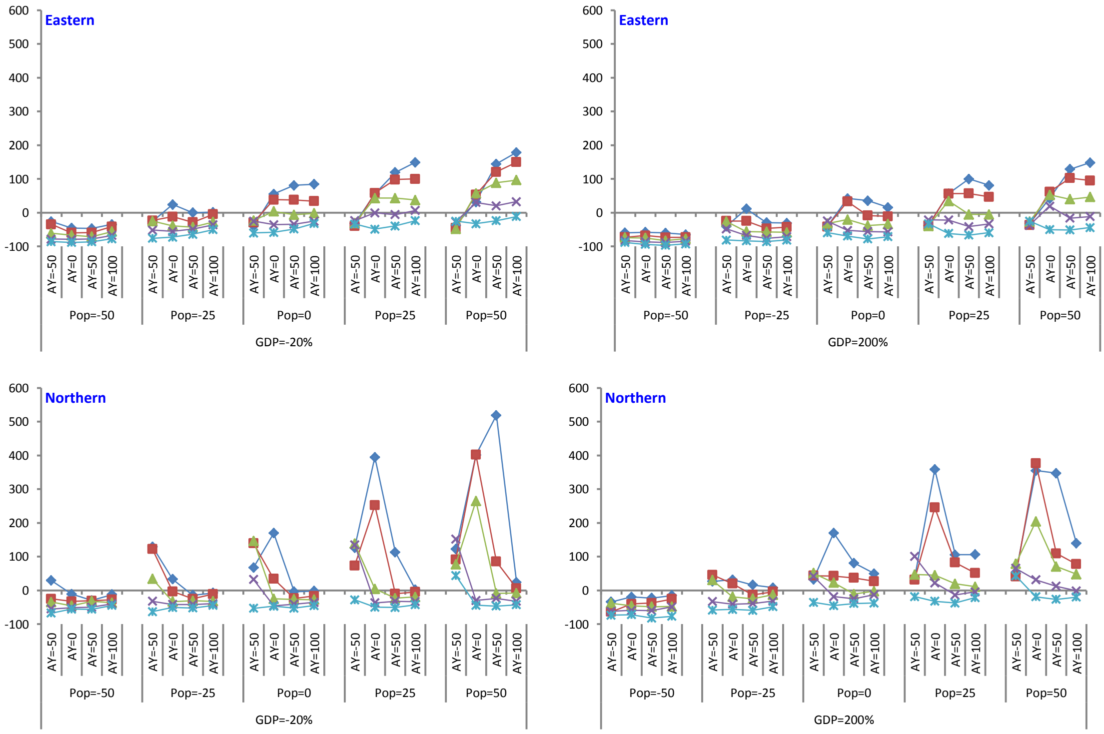
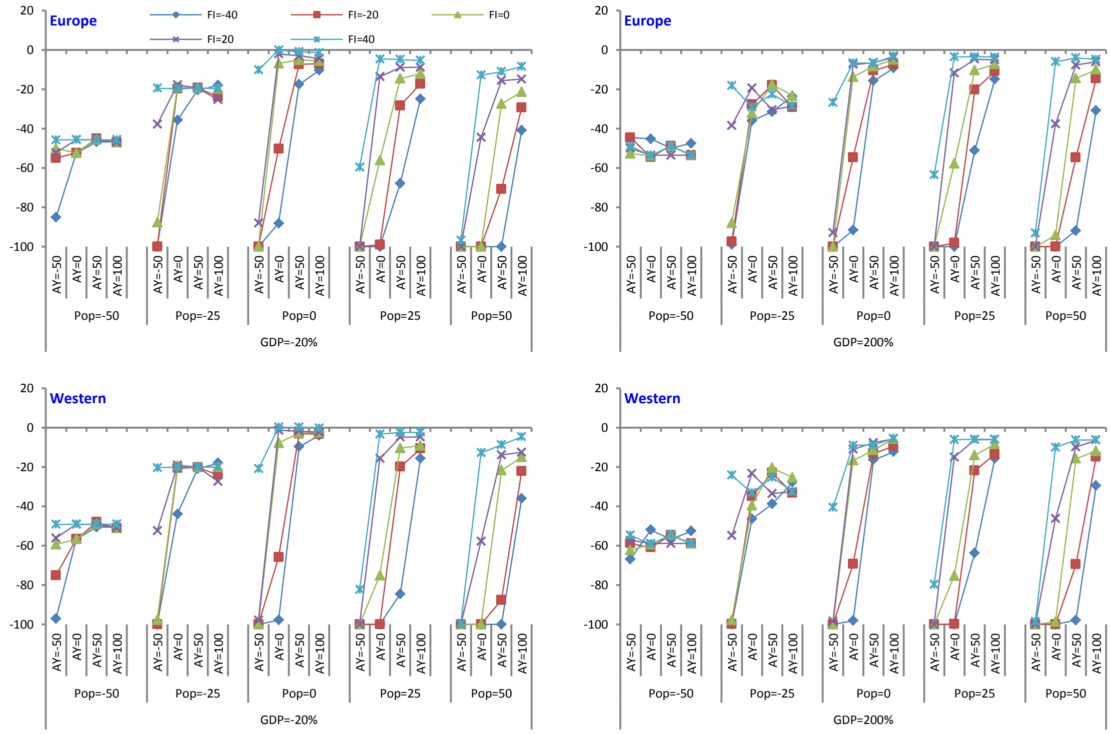


Figure 6.16: *Sensitivity of the % change of the regional total food production from baseline under various socio-economic scenarios.*

Figure 6.17 presents a summary of the sensitivity of TP to changes in the four socio-economic drivers under the various scenario combinations. TP is also sensitive to all of the four drivers due to their indirect implications through the effect on future land use change, particularly related to agricultural land use for FP. The indicator generally represents productivity of timber in each grid cell in terms of the managed forest that is profitable by combining the production of five representative species modelled (Table 4.1). In the current modelling system used within CLIMSAVE, the Europe-wide TP required is pro-rata with population and land which is not intensive arable or grass, can then be either extensive grass or managed forest based on profitability. In the same way as food demand, timber prices are adjusted to meet demand. However, as the land allocation model considers autonomous adaptation prioritising FP to meet demand, if food demand is high, it may not be possible to meet timber demand due to insufficient land availability for forest as land will be prioritised for agriculture. Hence, these have knock-on effects on future area of forest and associated TP. In addition, these indirect effects are significant and it is particularly hampered as the current modelling system does not allow to either change the species within a grid cell or to plant a species if there was none in a cell before.

The results show that most scenarios have negative impacts on TP, often due to either decrease in demand for timber (e.g., due to declining population) or the expansion of agricultural land use at the expense of forest areas (e.g., due to either increasing food demand or decreasing crop yields). Considering the effect of each of the drivers (i.e., GDP, population, agricultural yields, and food imports) independently (i.e., as in the ODAT analysis presented in Chapter 5), TP decreases in all regions under both increase and decrease in all drivers, except a small increase (by < 1%) due to increasing food imports (Figure 6.17). Generally, increasing population leads to an increase in food demand and hence expansion of agricultural land by also taking up forest areas which leads to a reduction in TP. Conversely, decreasing population leads to a decline in demand for timber and hence decline in production. Similarly, a decrease in food imports and agricultural yields leads to expansion of agricultural land to meet the existing food demand at the expense of forest area, which also leads to decline in TP. However, increases in food imports and agricultural yields have insignificant effect on TP as it doesn't affect both the demand for timber (which is driven by population change) or forest areas (which is indirectly affected by expansion in agricultural land – which also, in this case, do not change much) or timber yield (which is driven only by climatic drivers).

In contrast, when the combined effects of the drivers are considered for the European scale TP, the sensitivity range is estimated at 101% change from baseline (between mainly with a robust declining-trend with 100% loss of forest area under most of the scenarios to a 0.5% increase under a scenario with GDP=0%, Pop=0%, AY=0%, FI=+40%). The results also show similar trends and magnitudes of change in all regions, as in the case of the European results (Figure 6.17).



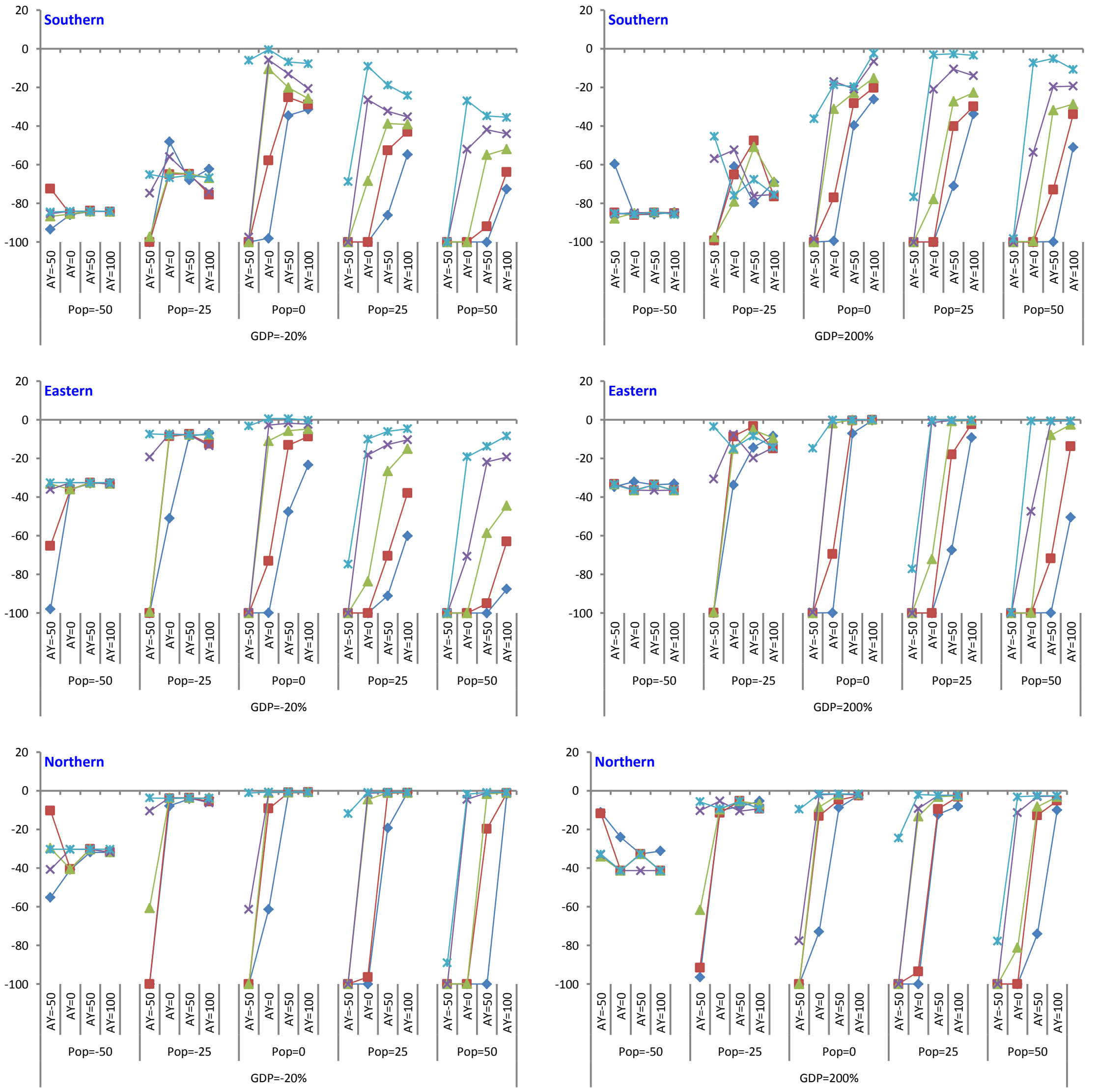
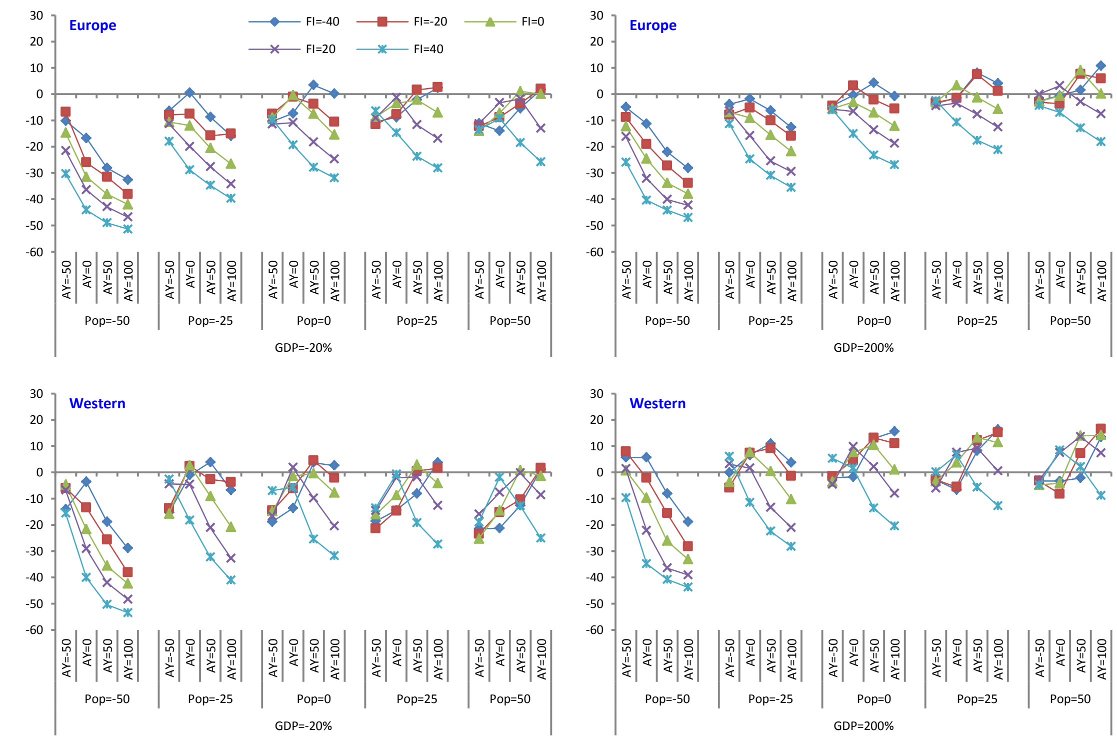


Figure 6.17: *Sensitivity of the % change of the regional total timber production from baseline under various socio-economic scenarios.*

Figure 6.18 presents a summary of the sensitivity of LUD to changes in the four socio-economic drivers under the various scenario combinations. LUD is a measure of multifunctionality of a landscape based on the Shannon Index of diversity. It represents proportions of six different land uses (urban, intensive arable, intensive and extensive grassland, forest and unmanaged land). Hence, the effect of the drivers under the various scenarios is related to the direct and indirect implications of the drivers on each of the above land uses. It generally shows complex changes due to changes in the drivers under the various scenarios. For example, when the effects of the individual drivers are considered, the Europe-wide LUD decreases from baseline under both increase and decrease in all the drivers. In terms of the magnitude of change, in contrast population followed by food imports have more pronounced effects on diversity than the other two drivers. The sensitivities are estimated between -31% and -9% (due to population change), -7% and -20% (due to change in food imports), -11% and -16% (due to change in agricultural yields), and between -0.5% and -3% (due to GDP change), under the extreme scenarios of each driver (Figure 6.18). However, there are some regional variations, particularly due to GDP change across all the regions as well as the effects of population, food imports and crop yields in northern Europe. Except in northern Europe (which shows similar trend as in Europe-wide changes), LUD increases with increasing GDP, particularly significantly in western Europe, which is partly associated with urban growth across the region. In contrast, increasing population or declining agricultural yields and food imports lead to increase in LUD, mainly due to expansion of agricultural land to new areas in the region (e.g., by replacing some forest areas, increasing LUD) as a result of the need to meet the growing food demand.

In contrast, when the combined drivers' effects are considered, the European scale sensitivity range is estimated at 64% change in diversity from baseline (between a 52% decline under a scenario with GDP=0%, Pop=-50%, AY=+100%, FI=+40% to an 11% increase under a scenario with GDP=+150%, Pop=+50%, AY=+100%, FI=-40%). The results also show similar trends and order of magnitudes of change in all regions as in the case of the European results – with the highest sensitivity estimated in northern Europe with a range of 75% (between -50% under GDP=-20%, Pop=-50%, AY=+100%, FI=+20% and +25% under GDP=+100%, Pop=+25%, AY=0%, FI=-40%). Whilst the least sensitivity is estimated in southern Europe with a range 63% (between -52% under the scenario of GDP=0%, Pop=-50%, AY=+100%, FI=+40% and +11% under the scenario of GDP=+200%, Pop=+50%, AY=+100%, FI=-20%; Figure 6.18).



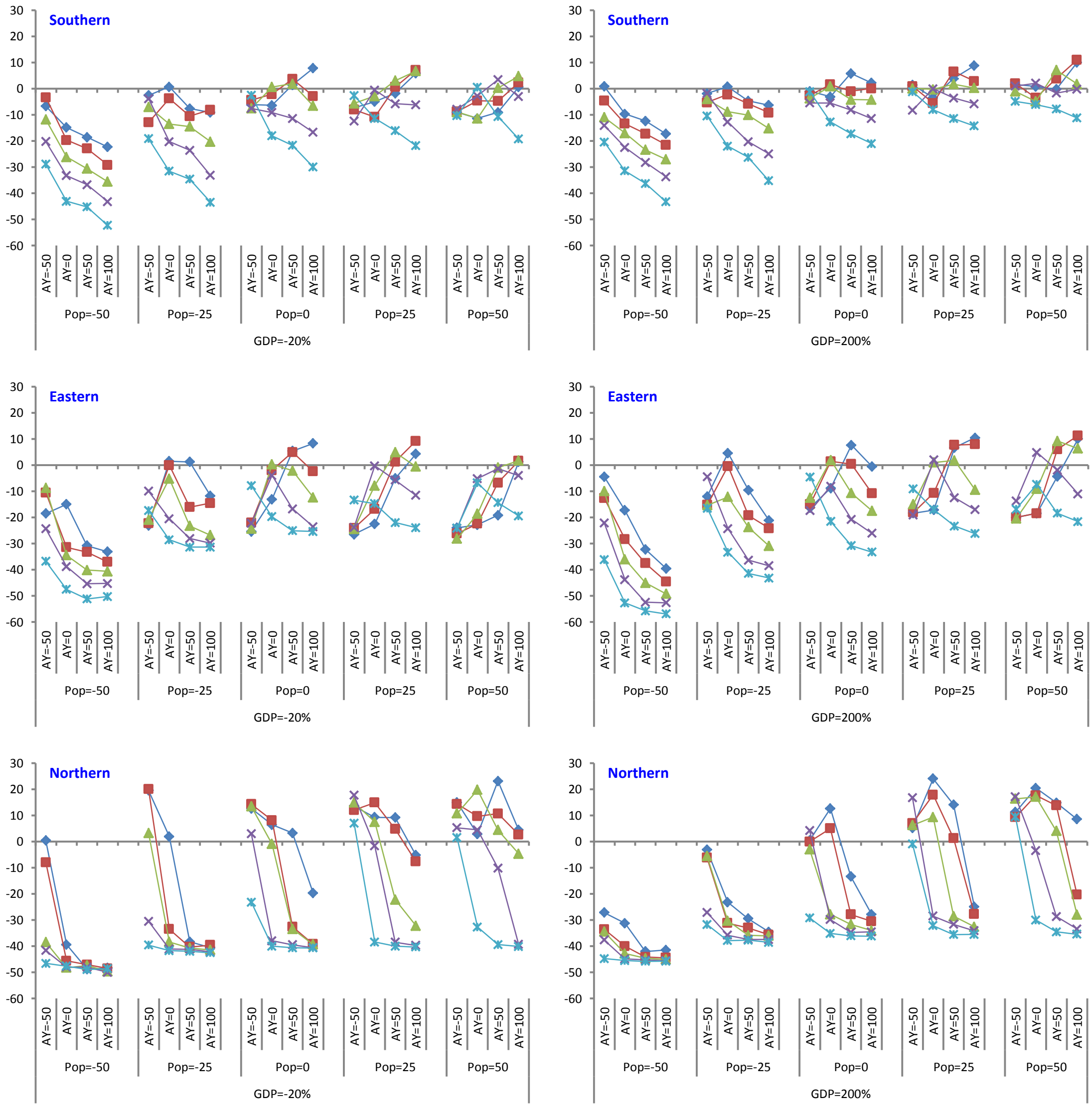
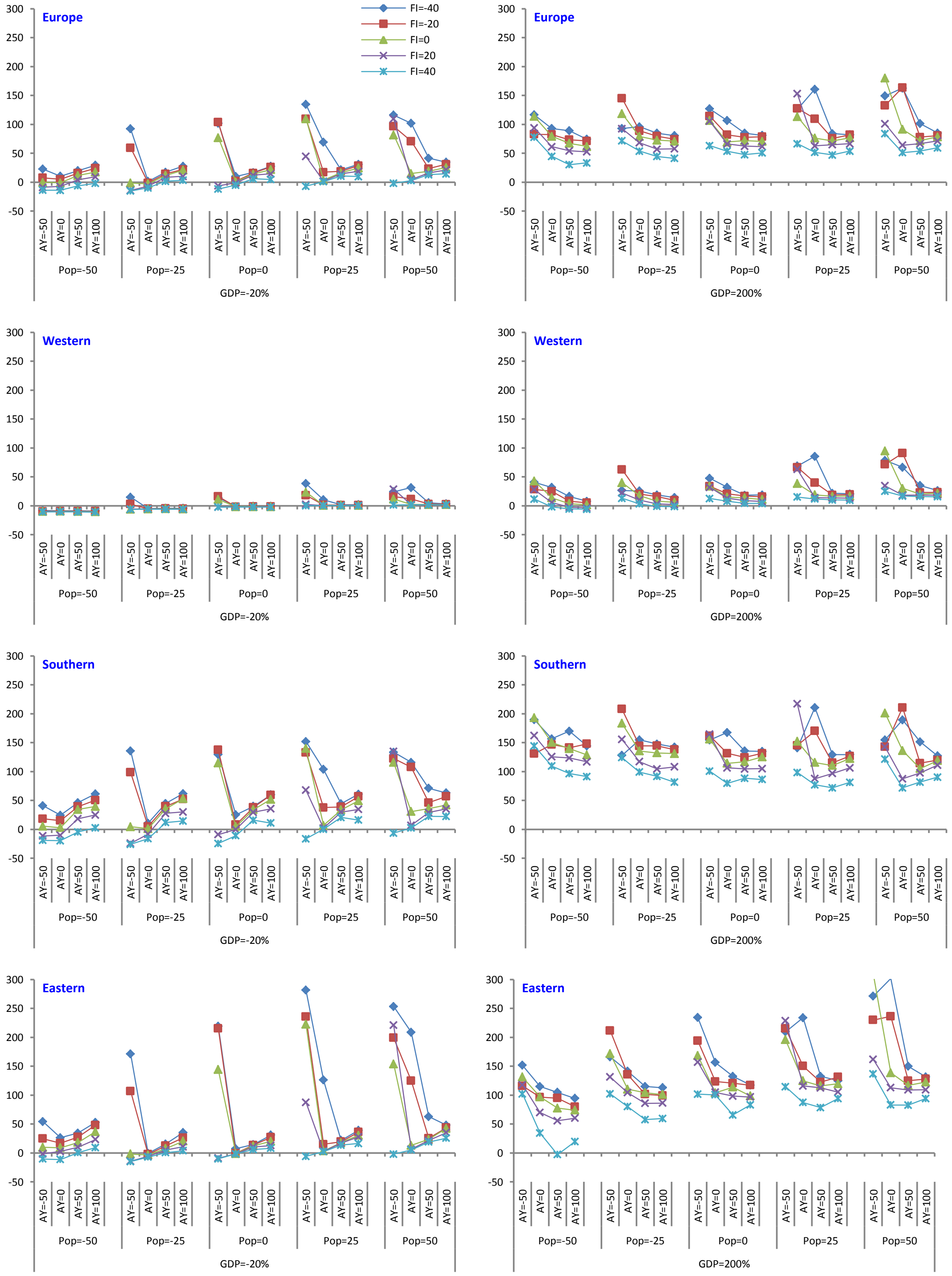


Figure 6.18: *Sensitivity of the % change of the regional average land use diversity from baseline under various socio-economic scenarios.*

Water exploitation index

Figure 6.19 presents a summary of the sensitivity of WEI to changes in the four socio-economic drivers under the various scenarios. The results show that WEI is sensitive to all the four drivers due to both direct and indirect implications on future water stress across Europe (affecting the demand side). The indirect effects are mainly through the implications of the drivers on irrigation water demand and use for agriculture. When considering the effect of individual drivers, the European scale WEI generally increases with both increase and decrease in all the drivers, except increasing food imports which leads to (small) decline in water stress (e.g., a 2.5% decline in WEI due to a 40% increase in imports). The highest increase in WEI (by up to 102% from baseline) is due to a (50%) decline in agricultural yields which leads to increased water use for irrigation to meet existing demand resulting in increasing in Europe-wide WEI. This is followed by a 70% increase in WEI due to a 200% GDP growth, which is mainly associated with the increase in domestic water use due to growing income within existing population resulting in, e.g., use of water-intensive appliances. In addition, a 50% population decrease/increase leads to an increase in WEI by up to 14%/20%, respectively. This is mainly due to increasing population leading to higher domestic water use in some regions leading to ↑ WEI, while a decline in population triggers rising irrigation water usage in some regions due to availability of more water for irrigation at lower prices as a result of a decrease in domestic water use. When the regional sensitivities are considered, similar patterns as in the European case are observed both in southern and eastern Europe. However, unlike other regions a positive correlation is observed between WEI and GDP and population in both western and northern Europe – where WEI increases with increasing GDP and population, and vice versa. In western Europe, the effect of GDP is more pronounced than population (e.g., +200 GDP leads to +15% WEI and +50% population leads to +7%), while the opposite is true in northern Europe (a +50% population leads to +14% WEI while a +200% GDP leads to +3% WEI).

However, when the combined drivers' effects are considered, there are complex interactions between the direct and indirect implications of the drivers resulting in both increase and decrease in WEI under the various scenarios. The European scale sensitivity range is estimated at 215% change from baseline, i.e., between a -15% (under the scenario with GDP=-20%, Pop=-25%, AY=-50%, FI=+40%) and a +200% (under the scenario with GDP=+100%, Pop=+50%, AY=-50%, FI=-40%). For the regions, eastern Europe is identified with the highest sensitivity range of 346% change from baseline, i.e., between -15% (under GDP=-20%, Pop=-25%, AY=-50%, FI=+40%) and +331 (under GDP=+100%, Pop=+50%, AY=-50%, FI=-40%). Southern Europe shows the second highest sensitivity with a range of 243% (i.e., between -26% and +217% change in WEI under scenarios of GDP=-20%, Pop=-25%, AY=-50%, FI=+40% and GDP=+200%, Pop=+25%, AY=-50%, FI=+20%, respectively). The least sensitivities are estimated in western and northern Europe with sensitivity ranges 133% (between -11% and +122%) and 139% (between -17% and +122%), respectively, across the scenarios.


Europe
FI=-40
FI=-20
FI=0
FI=20
FI=40
Western
Southern
Eastern
AY=-50
AY=0
AY=50
AY=100
Pop=-50
Pop=-25
Pop=0
Pop=25
Pop=50
GDP=-20%
GDP=200%

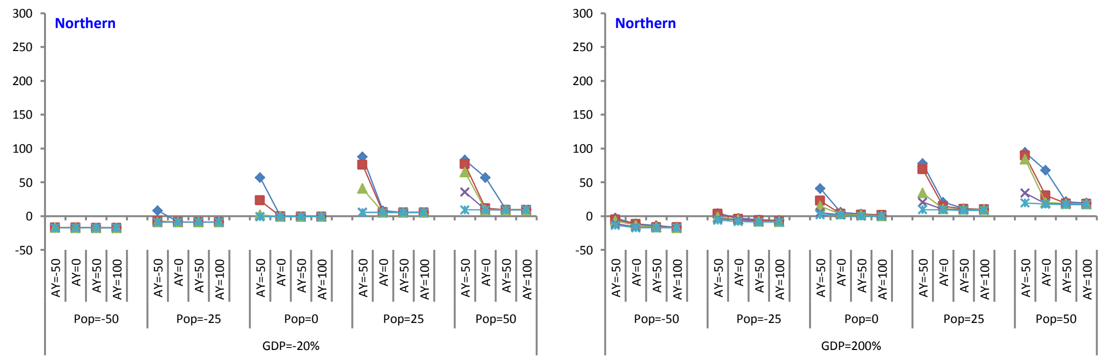


Figure 6.19: *Sensitivity of the % change of the regional average water exploitation index from baseline under various socio-economic scenarios.*

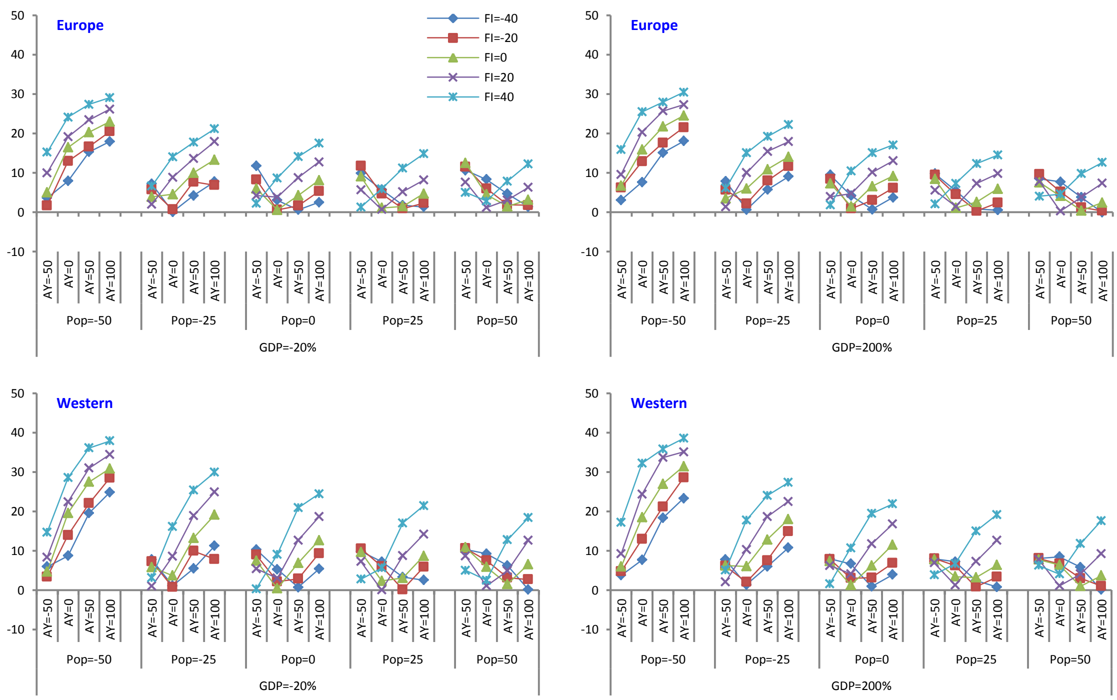
Biodiversity vulnerability index

Figure 6.20 presents a summary of the sensitivity of BVI to changes in the four socio-economic drivers under various scenarios. The results show that BVI is sensitive to all the drivers – which affect BVI indirectly through land use changes, particularly through the associated implications on arable farming related species. It is worth stating that these results mainly reflect the indirect effects of the drivers on the arable agriculture related species, and hence the behaviours observed and presented here are inherently limited to those species within the selected set of species considered in this analysis (totally 12; Table 4.1). The indirect implications on other types of species (e.g., not included here) could lead to sensitivity trends that are different from those presented here.

When considering effects of individual drivers, the European-wide BVI generally increases with both increase and decrease in all the drivers, with BVI varying between: +17% and 5% (due to -50% and +50% population change), +3% and 10% (due to -40% and +40% change in food imports), +5% and 8% (due to -50% and +100% change in agricultural yields), and +0.6% and 1.5% (due to -20% and +200% GDP change). Similar sensitivity trends are also observed across the regions – with the highest BVI increase estimated at 28% in eastern Europe, followed by a 19% increase in western Europe, both associated with a 50% decline in population. Although with varied magnitude of change, the exceptions in terms of the trends are in southern Europe, where BVI has positive correlation with GDP, agricultural yields and food imports and a negative correlation with population.

However, when combined drivers' effects are considered, there are complex interactions between the indirect implications of the drivers resulting in both increase and decrease in BVI under the various scenarios. Under some scenarios, there are complex biodiversity species' responses to the indirect implications of changes in the socio-economic drivers, as reflected in the ‘noisy’ pattern (e.g., higher population scenarios), while showing clear trends under ‘falling population’ scenarios (Figure 6.20). However, there is a ‘convergence pattern’ (e.g., development of an envelope) with increasing population. These patterns/distributions are generally true both at the European scale and across the regions, except northern Europe.

Moreover, in terms of the magnitudes of change, the results also show that there is generally an increasing-only change in BVI under most of the scenarios across the regions, except some small improvement in vulnerability under some scenarios. For example, the Europe-wide sensitivity range is estimated at 31% change in BVI from baseline, i.e., between -0.1% (under GDP=+50%, Pop=+50%, AY=0%, FI=+20%) and +31% (under GDP=+50%, Pop=-50%, AY=+100%, FI=+40%). For the regions, eastern Europe is identified with the highest sensitivity range of 48% change in BVI from baseline, i.e., between -1.3% (under GDP=-20%, Pop=-25%, AY=-50%, FI=+40%) and +47% (under GDP=+100%, Pop=+50%, AY=-50%, FI=-40%). Southern Europe shows the second highest sensitivity with a range of 46% (i.e., between -3% and +43% in BVI under scenarios of GDP=-20%, Pop=+50%, AY=+50%, FI=-20% and GDP=-20%, Pop=-50%, AY=+100%, FI=+40%, respectively). The least sensitivities are estimated in northern Europe with a range of 15% change from baseline (i.e., between -0.1% and +15%). In contrast, in western Europe, BVI shows a robust (increasing-only) change with a sensitivity range of 39% change in BVI from baseline, which varies between +0.1% (under GDP=-20%, Pop=+25%, AY=0%, FI=+20%) and +39% (under GDP=+50%, Pop=-50%, AY=+100%, FI=+40%).



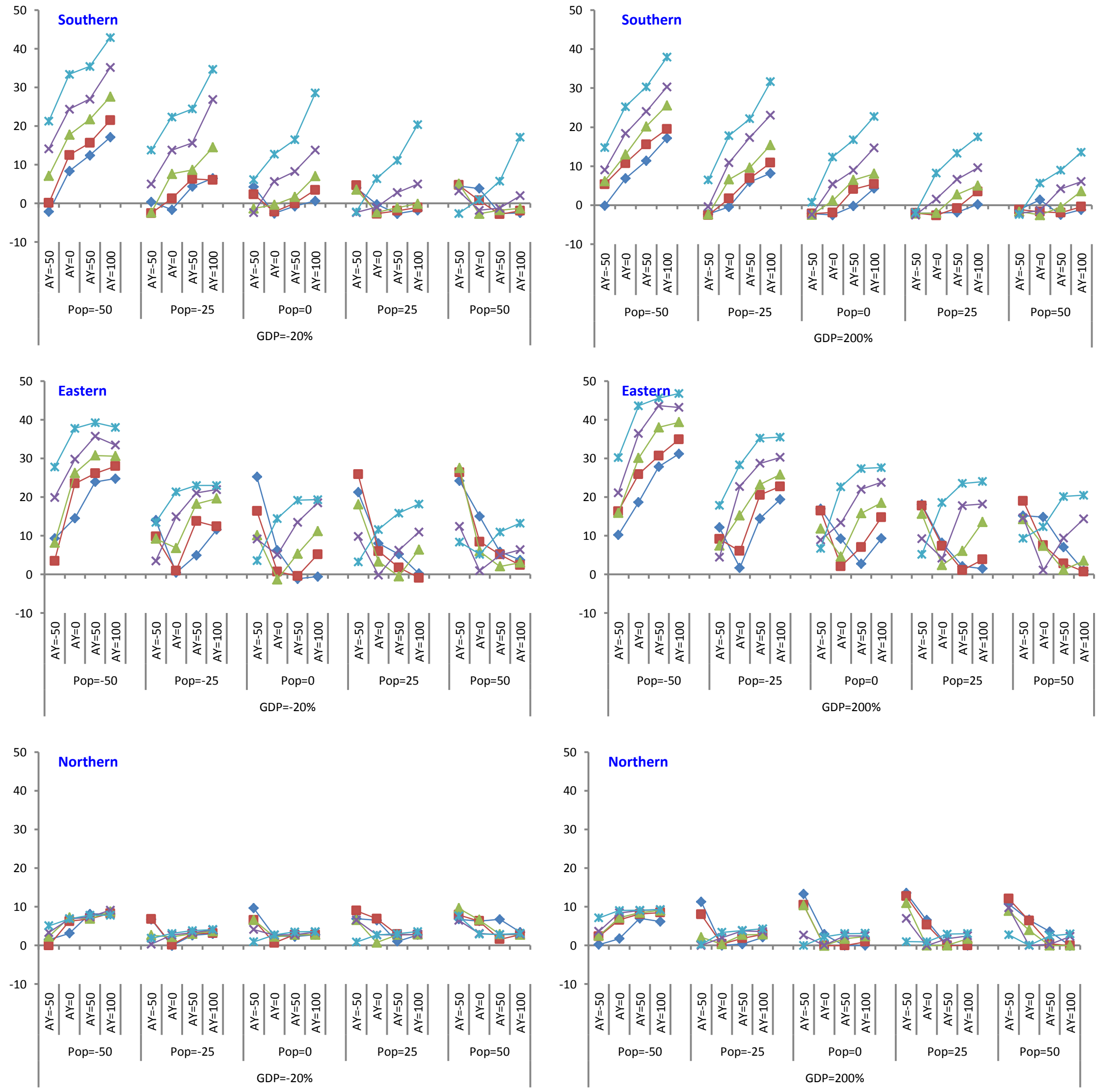


Figure 6.20: *Sensitivity of the % change of the regional average biodiversity vulnerability index from baseline under various socio-economic scenarios.*

6.4.2 Distribution of the grid-based impacts at the European scale

Figure 6.21 presents the Europe-wide percentile distribution of the indicators at the baseline (BL) and under the various socio-economic scenarios grouped by GDP change. There are significant variations in the distribution across the sectors/sub-systems and the scenarios as discussed below.

Artificial surfaces

For urban, the area of AS generally increases with increasing GDP, which leads to increased urban development. As the urban model is mainly driven by GDP growth, the highest increase in AS occurs under the scenario with a 200% increase in GDP, as reflected by the increase in the higher percentile distributions (Figure 6.21). While the 25th percentile is zero both at the baseline and under all future scenarios, the median value suggests that for about 50% of the grid cells at the European scale the percentage change in AS is <2.7% under all scenarios. However, although the regionally aggregated changes are relatively modest (especially when compared with other sectors/sub-systems), the results show that there are higher changes in AS locally as reflected by the extreme percentile distributions. For example, the 75th and 95th percentile grid cell values increases from 4% and 15% (baseline) up to 8% and 28%, respectively, under the scenario with the highest GDP growth (i.e., 200% increase from baseline).

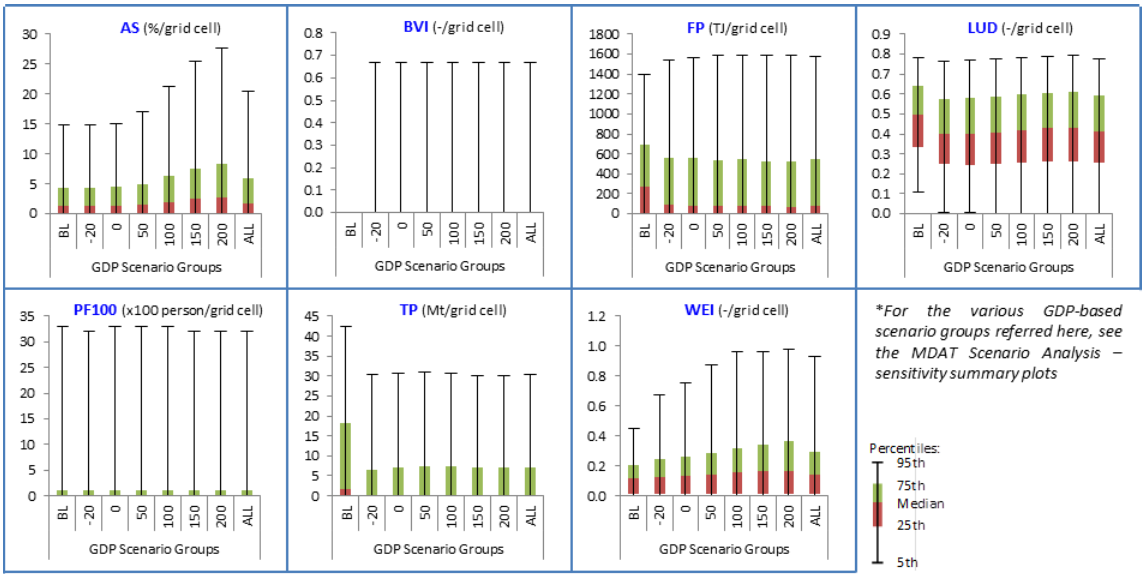


Figure 6.21: *European summary of the percentile distribution of indicators (per grid cell) at the baseline and across the various socio-economic scenarios grouped by GDP change scenarios.*

People flooded in a 1 in 100 year flood event

At the European scale, while almost 75% of the grid cells have no or less than 100 people flooded per grid cell by a 100 year event, PF100 is significant locally, as reflected by the 95th percentile distribution with grid cell estimates of more than 3,300 people flooded. It is worth stating that although the distribution of PF100 per grid is less sensitive to changes in GDP as shown by the unchanged (except a small decline) percentile coverage across the scenario groups, these results do not actually reflect the sensitivity of flood impacts to other socio-economic drivers, e.g., population change. This is due to the aggregation of the distributions associated with different population change scenarios presented based on the scenarios grouped by a number of GDP change projections (Figure 6.21). The linear relationship between population change and PF100 (Table 5.3) means that the GDP-based aggregation of the results cancel out the effects of a declining and increasing population scenarios of similar magnitude. These effects are discussed in Chapter 5. However, the results do demonstrate that impacts of flooding will remain locally significant under future scenarios.

Land use-related indicators: food production, timber production and land use diversity

At the European scale, the spatial distribution of FP per grid cell shows relatively small changes (from baseline) under the various socio-economic scenarios (Figure 6.21). The results show that the 25th percentile coverage is zero both at the baseline and across the different scenarios, reflecting that up to 25% of the grid cells are covered with non-agricultural land (e.g., urban areas). In contrast, the median grid cell value decreases from 275TJ (baseline) to just 70TJ, while the 95th percentile distribution show a small increase from 1,400TJ to 1,590TJ per grid under the scenarios with over 100% GDP growth. Similarly, the 75th percentile also declines on average by about 20% from 687TJ/grid (baseline) to 520TJ/grid across the scenarios, which also reflects that over 25% of the grid cells across Europe produce at least 500TJ/grid food under the future scenarios.

In contrast to the impacts of the climate change scenarios, there is a locally significant decline in TP under the socio-economic scenarios (Figures 6.21). The results show that, with the exception at the baseline, almost 50% of the grid cells across Europe have no TP, and are either covered by other land uses or existing forest area is lost to agriculture under the various scenarios. At the extremes, although the grid cell distribution are less sensitive to GDP change across the scenarios, the 95th percentile spatial coverage shows a decline by up to 12Mt timber per grid from baseline, which is mainly associated with the replacement of forest areas to agricultural use under future scenarios.

The Europe-wide LUD estimate also shows some variation in the spatial distribution of the proportion of the different land uses within a grid cell under the different scenarios. At the baseline, while each grid cell has at least more than one land use cover, over 50% of the grid cells in Europe have LUD greater than 0.5, which reflects the diversity of the spatial heterogeneity of the European landscape. Although there is a small increase in LUD with increasing GDP, the overall magnitude of the percentiles decreases from baseline marginally under all the scenarios, except for the extreme (95th) percentile under the higher GDP scenarios.

Water exploitation index

In comparison with the effect of the climate scenarios (Figure 6.11), WEI also shows significant variation under the various socio-economic scenarios, increasing with GDP growth (Figure 6.21). At the baseline, the Europe-wide 25th percentile distribution is estimated at <0.02, and stays the same under the GDP change scenarios, reflecting that there is no/very small water stress related issue in about 25% of the grid cells across Europe. In contrast, the 50th percentile is estimated at 0.12 (baseline), which is projected to grow by up to 5% under the highest GDP growth (200%↑). However, there are significant increases in water stress related issues locally (Figure 6.30). This is reflected by the extreme distributions, where the 75th and 95th percentile coverages are estimated at 0.21 and 0.45 (baseline) and significantly increase up to 0.36 and 0.98, respectively, under the scenario with a 200% GDP increase.

Biodiversity vulnerability index

Unlike the climate scenarios where there are improvements in BVI under some scenarios (particularly with increasing precipitation) (Figure 6.11), all the socio-economic scenarios have negative impacts on biodiversity (Figure 6.21). BVI is particularly significant locally, as reflected in the extreme distributions. The results show that, while the majority (about 75%) of the Europe-wide grid cells show no change in terms of the total number of species that are vulnerable, the 95th percentile coverage indicate that more than 65% the species in some particular places (over 5% of the European grid cells) no longer have suitable space in climate/habitat across the scenarios. These impacts of the socio-economic scenarios are particularly related to the indirect effects associated with land-use changes (e.g., agriculture) driven by, for example, changes in population or agricultural yields, which lead to the loss of arable-related species.

6.4.3 Distribution of the grid-based impacts at the regional scale

Similarly, when considering the regional percentile distributions, there are significant variations in the spatial distribution of the grid cell estimates of impacts across the various socio-economic scenarios (Figure 6.22).

Artificial surfaces

The results show that except in eastern Europe (where there are modest changes in the distribution of AS), there are significant increases from baseline with high variations in the spatial patterns of urban growth under the future scenarios. For example, in western Europe, as in the Europe-wide estimates, the percentile distribution of AS shows significant increase associated with high GDP growth across the region. While only 5% of the grid cells have no/unchanged AS in the regions, the 25th, median and 75th percentiles increase from 1.5%, 3.5% and 7.4% (at baseline) to up to 3.8%, 8.5% and 16.5%, respectively, under the scenarios with a 200% increase in GDP. This reflects that almost 25% of the grid cells will be covered by more than 16% AS. These estimates increase significantly locally in some grids cells, with the 95th percentile coverage increasing from 23% (baseline) to up to 42% under the highest GDP change (Figure 6.22). Similarly, in southern Europe while there are some changes in most of the grid cells, the extreme distribution indicates significant changes in AS, with the 95th percentile coverage increasing from 13% (baseline) to up to 26% under the 200% GDP growth. In northern Europe, while the % of AS at the baseline (in absolute terms) is relatively small when compared with other regions, the relative increase in the distribution (particularly at the extremes) is significant, as reflected by a 124% increase in the 95th percentile, from 6% (baseline) to over 13% under a 200% GDP growth.

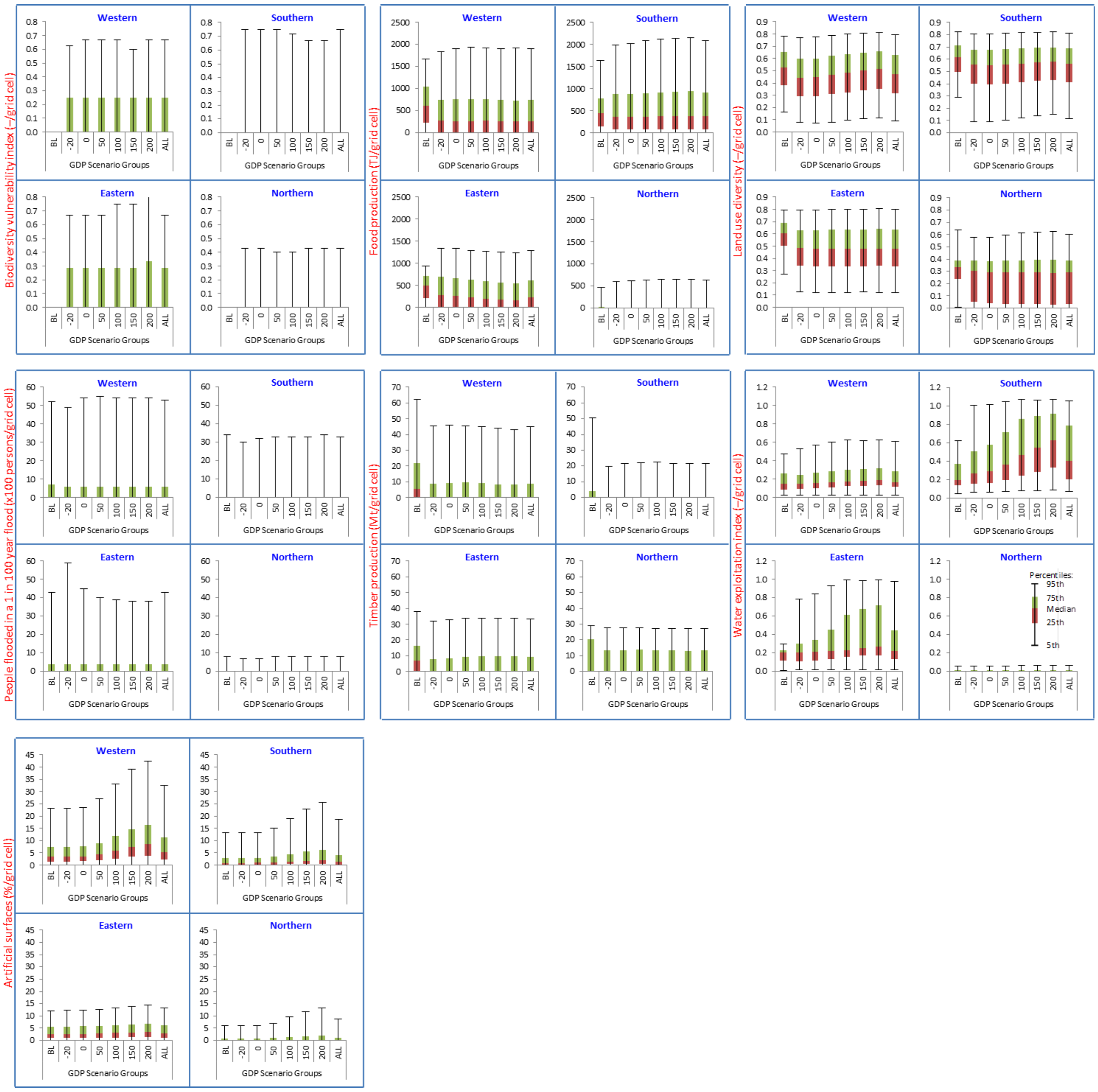


Figure 6.22: *Regional summary of the percentile distribution of indicators (per grid cell) at the baseline and across the various socio-economic scenarios grouped by GDP change scenarios.*

People flooded in a 1 in 100 year flood event

As in the Europe-wide estimates, the regional distributions of PF100 have local significance in all regions, except in northern Europe where impacts are relatively small (Figure 6.22). These patterns are similar to those associated with the climate scenarios. In comparison, the highest impacts of flooding are concentrated in western Europe (e.g., along the North Sea coast), with the 95th percentile estimated over 5,300 people per grid cell under most of the scenarios. However, when considering estimates under each scenario, the highest PF100 with the 95th percentile distribution is estimated in eastern Europe with up to over 5,900 people flooded per grid under the -20% GDP (Figure 6.31). When considering the regional average across the scenarios, the 95th percentile coverage is estimated at 4,300 and 3,300 people per grid in eastern and southern Europe, respectively, while in northern Europe these estimates reduce to just 800 people per grid cell.

Land use-related indicators: food production, timber production and land use diversity

At the regional scale, the spatial distribution of FP per grid cell shows varying changes across the regions and scenarios. Although at least 5% of the grid cells in each region cover non-agricultural lands, the distribution and magnitude of FP in western and southern Europe is generally higher than those in eastern and northern Europe (Figure 6.22). In western and southern Europe, although there are small changes in FP per grid from the baseline, there are no clear trends in terms of the median and 75th percentile distributions across the scenarios. However, the 95th percentile coverages in both regions show a positive trend with growing GDP; where the grid cell estimates of FP increase from 1,678TJ (in western Europe) and 1,640TJ (in southern Europe) (baseline) to 1,938TJ and 2,153TJ, respectively, under the +200% GDP. In northern Europe, while almost 50% of the grid cells are covered by non-agricultural land, most of the FP per grid is concentrated locally, with a small increase in the 95th percentile distribution from 460TJ/grid at the baseline to 650TJ/grid at the highest GDP scenario.

Unlike the climate scenarios, the regional scale percentile distribution in TP declines from baseline under the future socio-economic scenarios (Figures 6.22). These changes are significant locally, as reflected by the declines in the extreme percentile distributions. The results show that the median value in all the four regions is zero under all the scenarios, reflecting that in up to 50% of the grid cells in each region, there is either no TP even at the baseline (in southern and northern Europe, as indicated by the zero median value at the baseline) or there is a complete replacement of forest areas with other land uses such as agriculture (in western and eastern Europe), as indicated by the non-zero median at the baseline and zero median under future scenarios. In addition, in southern Europe the 100% decline in the 75th percentile coverage shows that there is also a removal of forest areas for agriculture in other areas in the region. When looking at the extreme distributions, the highest local change in TP occurs in southern and western Europe, with the 95th percentile declining from 50Mt/grid and 62Mt/grid at the baseline to 20Mt/grid and 43Mt/grid, respectively, under the various scenarios. In eastern and northern Europe, these declines are estimated at just 12% and 6%, respectively.

In terms of the regional scale LUD, the changes in the spatial distributions under the socio-economic scenarios (Figures 6.22) show generally similar pattern as that of due to the climate scenarios (Figures 6.12), reflecting complex changes in the various land uses across the regions. Although there are small changes, the distributions at the extremes (75th and 95th percentiles) are relatively unchanged (mainly <6% on average) across the scenarios. However, when looking at the changes particularly in the lower percentile distributions under the various scenarios relative to the baseline, there are significant declines in LUD across all the regions. The % decline in the median value from baseline is estimated at 21% (eastern), 13% (northern) and 10% and 8% in western and southern Europe, respectively. Even more significantly, the relative declines in the 25th and 5th percentiles are projected at 85% and 100% (northern), 18% and 60% (southern), 33% and 55% (eastern), and 16% and 44% (western) Europe, reflecting the wide spread of expansion of dominant land uses (e.g., agriculture) under most future scenarios resulting in a reduction in the overall diversity across the regions.

Water exploitation index

At the regional scale, the grid cell WEI estimates also show a significant variation in magnitude as well as spatial pattern of the percentile distribution across the scenarios and regions (Figure 6.22). The results show that southern Europe is the highest affected region, with a significant increase in the median value and the 25th and 75th percentile distributions under the various scenarios. At the baseline, more than 50% of the grid cells in the region have a WEI>0.2, which is projected to increase up to 0.6 under a +200% GDP. Similarly, the 25th and 75th percentile coverages increase from 0.14 and 0.37 (baseline) to 0.33 and 0.92, respectively, under the highest GDP growth scenario. Although there is a small difference in the distribution between the scenarios, the 95th percentile coverage also increases by over 70% from baseline, reflecting the overall increased pressure in natural water resources both locally and across the region. In eastern Europe, the median value and the 25th percentile coverage show only modest changes from baseline. However, the 75th and 95th percentiles increase dramatically from baseline by over 200% under the +200% GDP, reflecting that WEI is significant locally, distributed over 25% of the grid cells in the region. In contrast, while the changes in northern Europe are negligible (except a small change in less than 5% of the grid cells), there are relatively modest changes in western Europe, with the median and the 75th and 95th percentiles increasing by up to 20–30% under the scenario with 200% GDP growth, where over 50% of the grid cells have WEI>0.2.

Biodiversity vulnerability index

As in the Europe-wide changes, the regional scale BVI shows increasing-only trend across the regions (including northern Europe) under the socio-economic scenarios (Figure 6.22), unlike due to the climate scenarios where there are reductions in vulnerability under some of the scenarios (Figure 6.12). The results show that vulnerability increases significantly under all future scenarios, and are particularly important in local areas as reflected by the extreme percentile distributions across the regions. In southern and northern Europe, the median and the 75th percentile distribution are both zero, indicating that at least 50% of the grid cells in each region show no change in the number of species that are vulnerable to changes in the socio-economic drivers. However, the 95th percentile coverages are estimated with BVI>0.75 (southern) and 0.43 (northern) under some scenarios, reflecting that locally (in 5% of the grid cells in each region) over 75% and 43%, respectively, of the species in the regions no longer have suitable habitat space associated with land use change. In contrast, the higher 75th percentile grid cell BVI values of up to 0.3 in western and eastern Europe reflect that in over 25% of the grid cells in each region up to 30% of the species will lose appropriate habitat space. However, locally these figures increase significantly as reflected by the 95th percentile where on average (across all the scenarios) more than 60% of the species will no longer have appropriate habitat space as a result of significant land use changes in the regions.

6.5 Sensitivity of Cross-Sectoral Impacts due to Combined Climate and Socio-Economic Change Scenarios

Section 6.5.1 presents the potential interactions of the area-aggregated cross-sectoral impacts due to climate and socio-economic changes considering extreme scenario combinations. Then, Section 6.5.2 presents the percentile distribution of the grid-based changes in the indicators across Europe and the four catchment-based regions under the extreme scenarios.

6.5.1 Interactions of cross-sectoral impacts of climate and socio-economic changes

Various studies have highlighted the importance of sensitivity analysis to better understand whether or not interactions of the effects of individual drivers (or scenarios) are relevant (e.g., Anderson *et al*. 2012), i.e., whether or not the combined effects of different drivers (or scenarios) are equal to the summation of effects of the individual drivers (scenarios). This section illustrates the potential interactions of cross-sectoral impacts, based on an analysis of the individual and combined effects of selected extreme scenarios of climate and socio-economic changes. Table 6.3 presents ranking of the % change in indicators under four extreme scenarios of combined climate and socio-economic change driver combinations (i.e., Climate/Socio-economic: L/L, L/H, H/L, and H/H scenarios). In addition, for comparison purposes, the impacts under the individual extreme climate-only (CD) and socio-economic-only (SED) scenarios are also included. The table provides a useful insight regarding the potential interactions of impacts of future climate and socio-economic changes based on a comparison of the cross-sectoral impacts in terms of: (i) the summation of the impacts due to the individual scenarios (e.g., CD-L and SED-H) versus (ii) the total impacts with interactions under the combined scenarios (i.e., C&SED-L/H). The summary helps to better understand the nature of such interactions and the potential non-linear applications of future cross-sectoral impacts across sectors/sub-systems and regions.

Table 6.3: *European and regional ranking of the % change in indicators from baseline under the extreme climate and socio-economic scenarios and combinations.*

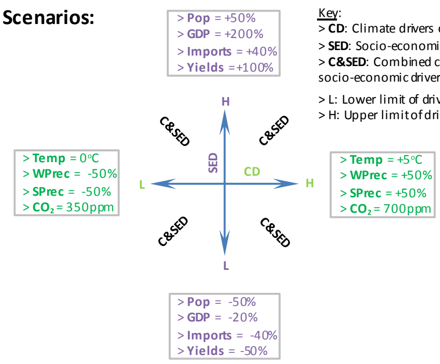
Indicators	Scenarios	Regions: EU	WE	SE	EE	NE	Comparison: CD+SED vs C&SED: EU	WE	SE	EE	NE
AS	CD-L	0.0	0.0	0.0	0.0	0.0	Urban: AS				
AS	CD-H	0.0	0.0	0.0	0.0	0.0					
AS	SED-L	0.0	0.0	0.0	0.0	0.0					
AS	SED-H	3.3	6.8	2.7	14	14					
AS	C&SED-L/L	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
AS	C&SED-L/H	3.3	6.8	2.7	14	14	0.0	0.0	0.0	0.0	0.0
AS	C&SED-H/L	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
AS	C&SED-H/H	3.3	6.8	2.7	14	14	0.0	0.0	0.0	0.0	0.0
BVI	CD-L	40.9	32.6	27.8	54.5	48.5	Biodiversity: BVI				
BVI	CD-H	16.1	43.8	37.6	21.2	-25.0					
BVI	SED-L	3.6	6.0	-2.1	9.3	15					
BVI	SED-H	12.6	17.6	13.6	20.5	3.0					
BVI	C&SED-L/L	34.3	30.4	21.3	36.8	44.2	-10.2	-8.2	-4.3	-27.0	-5.8
BVI	C&SED-L/H	53.3	46.4	35.4	84.1	52.6	-0.2	-3.9	-5.9	9.1	12
BVI	C&SED-H/L	15.8	36.1	41.9	34.2	-29.0	-4.0	-13.6	6.4	3.7	-5.5
BVI	C&SED-H/H	27.6	57.4	73.8	31.7	-29.4	-1.1	-4.0	22.6	-9.9	-7.4
FP	CD-L	0.0	-1.1	-8.0	3.6	29.3	Agriculture: FP				
FP	CD-H	-3.0	-13.0	-22.6	46.1	-9.4					
FP	SED-L	-27.1	-30.2	-33.6	-27.6	26.4					
FP	SED-H	-27.3	-47.8	25.9	-45.4	-21.8					
FP	C&SED-L/L	-31.2	-43.0	-45.3	-28.6	111.3	-4.1	-11.6	-3.7	-4.7	55.7
FP	C&SED-L/H	-26.7	-13.0	12.9	-97.1	-61.4	0.6	36.0	-5.0	-55.3	-68.9
FP	C&SED-H/L	-26.3	-20.9	-56.7	-18.3	28.8	3.8	22.3	-0.5	-36.8	11.9
FP	C&SED-H/H	-21.9	-46.4	-69.9	87.4	0.7	8.4	14.4	-73.2	86.7	32.0
LUD	CD-L	-13.0	-1.5	1.6	-13.3	-44.9	Diversity: LUD				
LUD	CD-H	-22.2	-19.9	-21.8	-5.0	-43.7					
LUD	SED-L	-10.2	-14.1	-6.7	-18.5	0.4					
LUD	SED-H	-18.1	-8.8	-11.2	-21.6	-35.4					
LUD	C&SED-L/L	-13.5	-12.5	-2.5	-27.5	-12.3	9.7	3.0	2.6	4.3	32.2
LUD	C&SED-L/H	-44.8	-16.4	-24.0	-75.4	-76.9	-13.7	-6.1	-14.4	-40.4	3.4
LUD	C&SED-H/L	-15.8	-10.6	-11.6	-13.1	-30.5	16.6	23.4	16.9	10.4	12.8
LUD	C&SED-H/H	-32.1	-34.0	-54.4	-6.4	-31.7	8.3	-5.3	-21.5	20.3	47.4
PF100	CD-L	-11.5	-8.4	-10.0	-19.3	-6.9	Flooding: PF100				
PF100	CD-H	7.6	9.0	4.1	9.3	1.5					
PF100	SED-L	-49.4	-50.5	-50.9	-46.2	-51.0					
PF100	SED-H	45.5	53.7	56.9	16.4	72.6					
PF100	C&SED-L/L	-55.2	-54.7	-55.9	-55.9	-54.4	5.7	4.2	5.0	9.5	3.4
PF100	C&SED-L/H	29.7	40.9	42.5	-6.6	60.4	-4.3	-4.4	-4.3	-3.7	-5.4
PF100	C&SED-H/L	-45.5	-45.9	-48.9	-41.4	-50.1	-3.8	-4.4	-2.1	-4.5	-0.7
PF100	C&SED-H/H	56.4	68.0	62.2	27.2	74.6	3.2	5.3	1.2	1.6	0.5
TP	CD-L	-99.7	-99.3	-100	-99.7	-100	Forest: TP				
TP	CD-H	5.6	-43.0	-82.1	91.7	63.4					
TP	SED-L	-85.1	-97.0	-93.4	-97.9	-55.2					
TP	SED-H	-4.8	-6.2	-10.7	-0.5	-2.6					
TP	C&SED-L/L	-100	-100	-100	-100	-100	0.0	0.0	0.0	0.0	0.0
TP	C&SED-L/H	-95.9	-91.2	-96.9	-99.6	-100	4.1	8.8	3.1	0.4	0.0
TP	C&SED-H/L	-45.8	-74.5	-89.7	11.9	-20.2	33.7	25.5	10.3	18.1	-28.4
TP	C&SED-H/H	69.9	-26.5	-64.6	181.2	204	69.1	22.8	28.2	89.9	143.2
WEI	CD-L	382	299	406.7	506.6	245.5	Water: WEI				
WEI	CD-H	-36.3	-39.6	-44.0	-19.2	-32.5					
WEI	SED-L	22.2	-8.2	39.2	53.8	-17.0					
WEI	SED-H	58.7	15.6	87.9	93.5	17.0					
WEI	C&SED-L/L	436	387	393	611.0	273.1	31.5	95.6	-52.7	50.6	44.5
WEI	C&SED-L/H	404	340	459.8	442.1	297.9	-37.0	25.3	-34.9	-158	35.4
WEI	C&SED-H/L	-40.0	-30.8	-56.2	-37.4	7.9	-25.9	17.0	-51.4	-72.0	57.4
WEI	C&SED-H/H	-12.3	-20.0	-43.4	47.1	5.1	-34.7	4.0	-87.3	-27.2	20.6

Ranking of the percentatge change values of indicators from the baseline estimates:

Indicators:
- >AS:–Artificial surfaces
- >BVI:–Biodiversity vulnerability index
- >FP:–Food production
- >LUD:–Land use diversity
- >PF100:–People flooded by 100 yr event
- >TP:–Timber production
- >WEI:–Water exploitation index

Regions:
- >EU:–Europe
- >WE:–Western Europe
- >SE:–Southern Europe
- >EE:–Eastern Europe
- >NE:–Northern Europe

Scenarios:



Key:
- > **CD**: Climate drivers only
- > **SED**: Socio-economic drivers only
- > **C&SED**: Combined climate and socio-economic drivers
- > L: Lower limit of driver range
- > H: Upper limit of driver range

Scenario definitions:
- >CD-L (H):–Low (High) Climate Drivers
- >SED-L (H):–Low (High) Socio-Economic Drivers
- >C&SED-L/L:–Low (Climate)-Low (Socio-Economic) Drivers
- >C&SED-L/H:–Low (Climate)-High (Socio-Economic) Drivers
- >C&SED-H/L:–High (Climate)-Low (Socio-Economic) Drivers
- >C&SED-H/H:–High (Climate)-High (Socio-Economic) Drivers

Driver definitions:

CD:
- >Temp: Temperature ch. ($0^{o}C$)
- >WPrec: Winter precipitation ch. (%)
- >SPrec: Summer precipitation ch. (%)
- >CO_2: CO_2 concentration (ppm)

SED:
- >Pop: Population ch. (%)
- >GDP: GDP ch. (%)
- >Imports: Ch. in food imports (%)
- >Yields: Ch. in agricultural yields (%)

Ranking of % change of indicators:

0 – 5	No	No/Insignificant change
5 – 50	L	Low
50 – 100	M	Medium
≥ 100	H	High

Ranking colour code:

Increase		[For BVI, PF100, WEI]				Decrease
H	M	L	No	L	M	H
Decrease		[For AS, FP, TP, LUD]				Increase

KEY:

H	M	L	No	L	M	H
Increase						Decrease

=====> Comparison check for linear function: C&SED = CD + SED?

Rank:

0 – 5	No	No/Insign. Ch.
5 – 50	L	Low
50 – 100	M	Medium
≥ 100	H	High

The results demonstrate that impacts of the combined (C&SED) scenarios are not always equal to the linear sum of the impacts due to the independent CD and SED scenarios, and they have varied effects across the sectors/sub-systems and regions. This is particularly important for WEI, FP, and TP, and to some extent to BVI and LUD (Table 6.3, right columns). For example for FP in northern Europe, while it is estimated to increase by 29% and 26% (from baseline) under the CD-L and SED-L extreme scenarios, respectively, the projection increases rather dramatically to over a 111% increase under the combined C&SED-L/L extreme scenarios. This is a 56% relative difference (increase) under the combined scenario effects more than that of the sum total of the individual scenarios. Also, the SED-H scenario leads to a 22% decline in FP (from baseline), but under the combined C&SED-L/H scenario FP declines by 61%, with a total relative difference of 69% between the combined and sum of individual scenarios. In contrast, WEI shows the most non-linear variation of these impacts, with mostly medium to high percentage difference in water stress due to the combined effects relative to the sum of the individual scenarios. These results generally illustrate the complex and 'non-additive' nature of the interactions of impacts due to the climate and socio-economic drivers and associated differences both in magnitude and directions of change in impacts. In contrast, for AS, PF100 and BVI (with few exceptions with some medium non-linearity), there is an almost linear relationship between the impacts of the combined and sum of individual scenarios.

Furthermore, the results show that although there are significant variations in terms of the magnitudes of change, most sectors/sub-systems experience worsening (negative) impacts (shown in red) under most of the extreme scenarios in most of the regions, with the exceptions shown in blue (Table 6.3, left columns). For example, WEI and TP, in contrast, are projected with the highest (≥ 100%) change from baseline in all regions under one/more of the extreme scenarios. For WEI, there is uncertainty in the directions of change in all regions except northern Europe, with the highest sensitivity estimated under the CD scenarios when compared with that of the SED scenarios. Under the low climate scenarios (i.e., C&SED-L/L and L/H), there is a significant projected water stress across all regions, with an increase in WEI by more than 270% from baseline (dark red). However, under the high climate scenarios (i.e., C&SED-H/L and H/H), the sensitivity of WEI varies between low to medium (mainly declining) changes across the regions: WEI declines by 12% to 56% in western and southern regions as well as at the European level, and increases by up to 8% in northern Europe. In eastern Europe, the extreme SED scenarios have varied effect on WEI, resulting in a 37% decline under the C&SED-H/L scenario and a 47% increase under the C&SED-H/H scenario.

Similarly for TP, the extreme low combined scenario (i.e., C&SED-L/L, which, for example, includes a 50% decline in both precipitation and population) has significant negative implications, leading to a 100% decline in TP from baseline across all regions. This is mainly due to, for example: (a) declining demand for timber due to the decrease in population and (b) declining forest areas associated with an increase in agricultural land at the expense of forest areas in order to increase FP to meet demand under falling productivity due to a decline in precipitation. In contrast, under the combined extreme C&SED-H/H scenario, there is a significant TP increase from baseline, particularly in eastern and northern Europe (by more than 180%), as well as a medium European scale increase by about 70%. These changes are mainly driven by an increase in timber yield as a result of increasing CO_2 as well as increasing demand for timber due to increasing population in areas with high timber productivity and profitability than agriculture. Oppositely, while there is generally a low to medium change in FP under most of the extreme scenarios in all regions, the highest relative increase (by more than 111% from the baseline) is observed in northern Europe under the combined extreme C&SED-L/L scenario. This mainly illustrates the northward shift in agriculture under the relatively warmer climate scenarios.

In contrast, PF100 estimates range between low and medium changes from baseline across all regions under most of the extreme scenarios. This is particularly true for the high socio-economic scenarios, with the highest relative change in PF100 estimated in northern Europe by up to 75% increase (from baseline) under the combined extreme C&SED-H/H scenario. In contrast, there is generally a low to no change in BVI and LUD under most of the scenarios across all regions, with few exceptions. For BVI, while there is a small improvement in northern Europe under high climate scenarios (CD-H, C&SED-H/L and H/H), the highest BVI increase is estimated in eastern Europe (with +84% from baseline under the C&SED-L/H scenario) followed by southern Europe with +74% under the C&SED-H/H scenario. Similarly, the C&SED-L/H scenario has a medium effect for LUD, leading to over +75% from baseline in eastern and northern Europe regions. In contrast, AS shows no change under both the low and high climate as well as the low socio-economic change related extreme scenarios. However, there is a projected increase in AS under the high extreme socio-economic change related scenarios, with the highest urban growth estimated in western Europe by about 7%, while increasing by just over 3% at the European scale. However, these projected urban changes are relatively low/small (negligible) in magnitude when compared with other sectors/sub-systems.

6.5.2 Distribution of the grid-based impacts at the European scale

Figure 6.23 presents the Europe-wide percentile distribution of the grid cells values of the indicators under the extreme scenarios of (i) climate-only (CD), (ii) socio-economic-only (SED), and (iii) combined climate and socio-economic (C&SED) scenarios. Analysis of such estimates allows comparing impacts within and across the climate and socio-economic scenarios and across sectors/sub-systems. The results also highlight the fact that not all extreme scenarios lead to extreme effects across all sectors/sub-systems relative to other lower scenarios, where impacts in some sectors/sub-systems under such scenarios can be the highest when compared with those estimates under the extremes, as discussed below.

Artificial surfaces

At the European scale, the median value of AS is less than 3% both at baseline and across the various extreme scenarios, reflecting that in at least 25% of the grid cells across Europe there is only very small change in AS. As discussed in previous sections, Figure 6.23 also shows that the distribution of urban growth is sensitive only to changes in the socio-economic scenarios, and is not sensitive to the climate drivers. The 75^{th} percentile distribution is estimated between 4% and 9%, showing a modest increase from the baseline by about 5% under the SED(H) scenario. This is mainly associated with the 200% GDP growth from baseline. However, the percentile estimates at the extreme distribution indicate that the major urban growth is mainly concentrated in only about 25% of the grid cells across Europe, as reflected by the 95^{th} percentile coverage of AS per grid cell estimated at more than 28% of residential and non-residential areas, increasing by over 13% from the baseline.

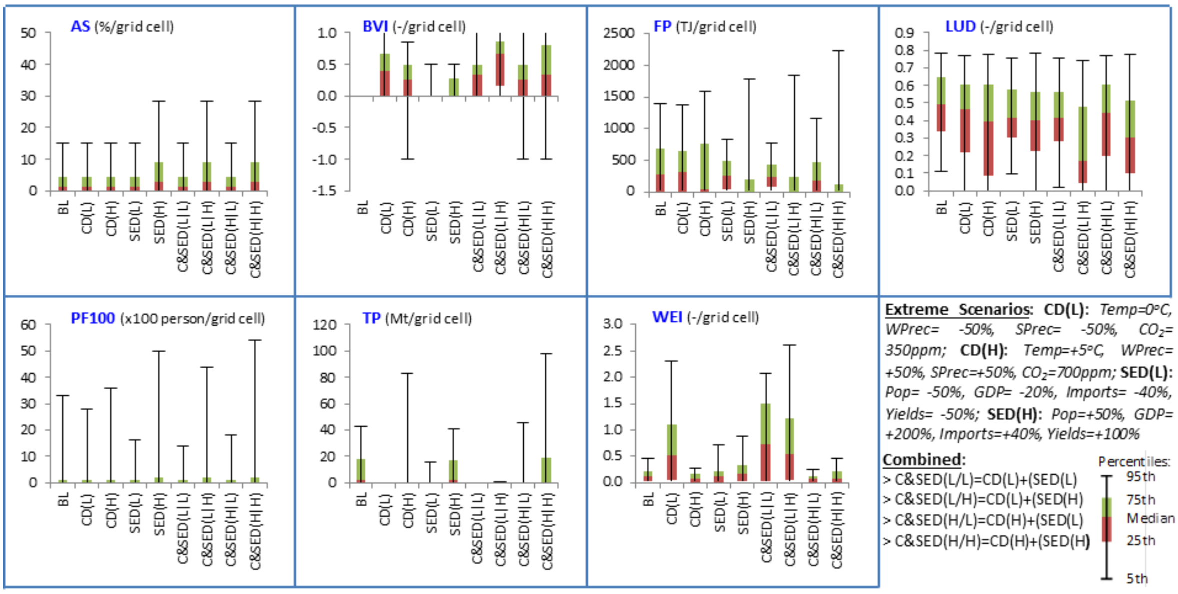


Figure 6.23: *European summary of the percentile distribution of indicators (per grid cell) at the baseline and across the combined climate and socio-economic extreme scenarios. Note that the*

percentile distributions due to the climate-only (CD) and socio-economic-only (SED) extreme scenarios are also included for comparison.

People flooded in a 1 in 100 year flood event

Although different in magnitude, PF100 increases under the upper bounds of the extreme C&SED scenarios (Figure 6.23). In contrast, while the Europe-wide changes are generally modest, they are locally significant, as reflected by the extreme percentile distributions. In addition, the results demonstrate that these local impacts are much higher under the extreme socio-economic scenarios than due to the climate scenarios. At the lower end, the 95th percentile coverage declines from 3,330 people (baseline) to 1,400 people (i.e., a 58% decline) under the extreme C&SED(L/L) scenario. At the higher end, the 95th percentile increases by 64% from the baseline up to 5,400 people flooded per grid under the extreme C&SED(H/H) scenario. These impacts are mainly attributed to the combined effect of a 50% increase in population as well as summer and winter precipitation.

Land use-related indicators: food production, timber production and land use diversity

At the European scale, both the median and the 25th percentile distributions show that both the current and future FP in almost 50% of the grid cells will not exceed estimate of 350TJ/grid under the various extreme scenarios (Figure 6.23). In addition, when looking at the 75th percentile coverage, FP per grid declines from baseline under almost all the extreme scenarios, ranging between -6% (under the CD(L) scenario) to -82% (i.e., from 687TJ/grid (baseline) to just 127TJ/grid under the C&SED(H/H) scenario). The exception is the CD(H) scenario, where there is a projected 10% increase in FP, associated with the increase in productivity in some areas due to increased precipitation. However, the 95th percentile coverage shows that there are significant changes locally, associated with changes in productivity and/or demand under the various extreme scenarios. The results show that the lower bound extreme scenarios (both the climate and socio-economic drivers) lead to a decline in FP by up to 45% under the C&SED(L/L) scenario, as a result of a reduction in food demand (associated with a 50% decline in population under the scenario) as well as a decline in production due to declining precipitation. In contrast, the 95th percentile increases by up to 60% under the C&SED(H/H) scenario resulting in a significant increase in demand (e.g., due to 50% population increase) and production (e.g., due to increased precipitation such as in northern Europe).

The Europe-wide TP generally declines under most of the extreme scenarios as a result of loss of forest areas (e.g., taken up by agriculture), except in some areas as reflected by the extreme percentiles (Figure 6.23). The 95th percentile distribution shows that the grid cell estimates of TP in 5% of the grid cells across Europe show an increase from baseline associated with the upper bound climate driver extreme scenarios. For example, under the CD(H) scenario, the 95th estimate increases by over 95%, which is mainly driven by the increase in CO_2 that improves timber productivity. However, under the C&SED(H/L) scenario the increase is estimated at just 9%, indicating that although there is an improvement in timber productivity due to CO_2 increase, the total production is reduced due to the decline in demand for timber associated with the decline in population under the SED(L) scenario. This is also reflected by the significant increase (by more than 130% from baseline) in the 95th percentile under the C&SED(H/H) scenario, which leads to an increase in both productivity and demand.

The change in spatial distribution of LUD also reflects the complex nature of the interactions between various land uses under the different extreme scenarios. The results show that there will be a decline in diversity, as reflected by the overall decrease in the percentile distributions from the baseline under the different scenarios (Figure 6.23). On average, the declines in the percentiles are estimated at: -2% (95th percentile) and -13% (75th percentile) to -46% (25th percentile) and -87% (5th percentile). The median value also suggests that about 50% of the Europe-wide grid cells experience a decline in LUD by about 24%, which ranges between -7% (under the CD(L) scenario) to -66% (under the C&SED(L/H) scenario). These results reflect that there is an overall decline in diversity associated with an expansion of dominant land use(s) across Europe, while the spread of the distribution suggesting that different land uses dominate the coverage in different regions.

Water exploitation index

Considering the various extreme scenarios, the change in the distribution of WEI estimates per grid across Europe is mainly driven by changes in the climate drivers (i.e., precipitation and temperature), as indicated by the significant increase in WEI under the lower bound climate scenarios (Figure 6.23). These changes are particularly significant locally, which are reflected by the change in the extreme percentile (75th and 95th) distributions. The highest increase in the median and 75th percentile coverage is projected under the combined C&SED(L/L) extreme scenario, increasing (from baseline) by over 500% and 620%, respectively. These WEI increases are mainly associated with the significant (by 50%) decline in precipitation, which results in a reduction in water availability in some regions such as southern Europe. In contrast, the highest increase in the 95th percentile is due to the C&SED(L/H), estimated with over 480% increase from baseline due to the 50% decline in precipitation (reducing water availability) as well as a 50% population increase and 200% GDP growth (leading to an increase in water use through, for example, increased demand (due to more people) and use of water-intensive appliances by wealthier population).

Biodiversity vulnerability index

The BVI increases significantly under the low climate and both low and high socio-economic extreme scenarios, while showing a major improvement in vulnerability under the upper bound climate driver extreme scenarios regardless of the effect of the lower and upper bound socio-economic drivers (Figure 6.23). Except under the C&SED(L/H) scenario where BVI is estimated at 0.2 (i.e., 20% of species losing suitable habitat space), 25% of the grid cells across Europe show no change in vulnerability. Under the SED(L) and SED(H) scenarios, both the median and 25th percentile are zero, reflecting that 50–75% of the grid cells in Europe show no change in the number of vulnerable species. However, the changes in BVI under these scenarios are locally significant, as shown by the 95th percentile distribution where over 50% of the species in 5% of European grid cells will no longer have a suitable habitat space. The results also demonstrate that the highest change in BVI occurs mainly at the extremes (i.e., 5th and 95th percentiles) and driven mainly by the climate drivers. For example, under the upper bound climate scenarios (i.e., CD(H), C&SED(H/L) and C&SED(H/H)), there is a divergence in the distribution at the extremes, as reflected by a significant decline in the 5th percentile (with BVI=-1) and increase in the 95th percentile (i.e., BVI>0.9). These changes are associated with both the direct effects on availability of appropriate climate space and the indirect effects on availability of appropriate habitat space through land use changes.

6.5.3 Distribution of the grid-based impacts at the regional scale

Figure 6.24 presents the regional scale percentile distributions of the indicators at the baseline and under the various extreme climate and socio-economic scenarios. The results show significant variation in the distribution across the sectors/sub-systems, regions, and scenarios.

Artificial surfaces

While there are significant variations in magnitude across the regions, as in the European case, the regional scale changes in AS are also mainly driven by changes in socio-economic drivers (e.g., GDP change). These are particularly higher locally in some areas under the upper bound extreme SED scenarios (Figure 6.24). As discussed in Sections 6.4.2/6.4.3, the 75th and 95th percentile distributions increase from the baseline by up to 10% and 20% (western) and 3% and 12% (southern Europe). Although the changes (from baseline) at the extremes are also locally important, the changes in northern Europe are relatively marginal when compared with other regions.

Figure 6.24: *Regional summary of the percentile distribution of indicators (per grid cell) at the baseline and across the combined extreme climate and socio-economic scenarios. Note that the percentile distributions due to the climate-only (CD) and socio-economic-only (SED) extreme scenarios are also included for comparison.*

People flooded in a 1 in 100 year flood event

As in the European case, the regional PF100 also have local significance, as indicated by the extreme percentile distributions (Figure 6.24). The results show that PF100 declines in all regions under the lower boundary of the climate and socio-economic scenarios (CD(L) and SED(L)), while increasing significantly under the upper bound scenarios (CD(H) and SED(H)). The results also reflect that PF100 is mainly driven by the socio-economic scenarios: e.g., in western Europe, the changes in the 95th percentile from baseline are estimated between -49% and +62% under the lower and upper extreme socio-economic scenarios, respectively, while changing by just -14% and +11% under the lower and upper extreme climate scenarios. In addition, in western and southern Europe the 95th percentile coverage declines by up to 57% (i.e., from 3,700 people/grid at baseline to 1,600 people/grid under the C&SED(L/L) scenario), while increasing by over 76% (i.e., up to 6,500 people/grid under the C&SED(H/H) scenario). However, it is worth noting that at the extremes the maximum PF100 per grid also reaches up to 124,100 (western) and 284,200 people (southern) under the C&SED(H/H) scenario. The highest increase from baseline in the 95th percentile in eastern and northern Europe is also estimated at 67% and 41%, respectively.

Land use-related indicators: food production, timber production and land use diversity

The regional level FP is also highly sensitive to the extreme scenarios, although with varied level of change in the distributions across the regions (Figure 6.24). As in the European case, the 5th percentile shows that about 5% of the grid cells in each region are covered by non-agricultural land such as urban/forest areas. Furthermore, when considering the median and 25th percentile coverages, there is no FP in at least 25% of grid cells in each region under some of the extreme scenarios, such as (i) the upper bound extreme climate scenario (e.g., increased precipitation) leading to an increase in productivity where less productive areas are abandoned and more of the production made in more productive areas, or (ii) the upper bound socio-economic extreme scenarios (e.g., increased food imports) leading to a decline in production in some areas. In contrast, at the extremes there is a significant increase in FP locally, where the highest is estimated in northern and western Europe, as reflected by the 145% (from 960 to 2,336 TJ/grid) and 125% (from 1,429 to 3,247 TJ/grid) increase in the 95th percentile from baseline, respectively (under C&SED(H/H) scenario). However, in southern Europe there is a 50% (from 1,626 to 792 TJ/grid) decline in the 95th percentile under the same scenario, associated with a decline in productivity in the region under a hot future climate.

However, for TP, the results show that there is a significant removal of forest areas per grid across the regions under all the extreme scenarios, except in few areas as reflected by the 95th percentile distribution (Figure 6.24). The 25th percentile and median values show that TP is zero in 25–50% of the grid cells in each region as it is often taken up by agricultural land use to meet food demand under all of the extreme scenarios which result in either declined productivity and/or increased demand for food. However, there are some increases in TP under some scenarios, as reflected by the relative increase in the 95th percentile from baseline by up to 170% (from 42 to 113 Mt/grid), 154% (from 33 to 83 Mt/grid) and 130% (from 46 to 106 Mt/grid) in northern, eastern and western Europe, respectively, under C&SED(H/H) scenario.

The complex land use changes under the various extreme scenarios are also reflected in the varied changes in the spatial pattern of the LUD percentile distributions (Figure 6.24). Generally, there is a declining pattern in the distribution in at least 50% of the grid cells in each region, as reflected by an average of a 25% decrease in the median values across all the extreme scenarios. The overall decrease in LUD across the regions indicates that the extreme scenarios lead to expansion of dominant land uses at the expense of other land uses resulting in a decline in diversity.

Water exploitation index

The regional WEI percentile distribution also increases under both of the extreme socio-economic scenarios (SED(L) and SED(H)) and the low extreme climate-related scenarios (CD(L), C&SED(L/L) and C&SED(L/H)), while declining under the other extreme scenarios (Figure 6.24). The highest increase (from baseline) is estimated in southern and western Europe, where the 75th and 95th percentile coverages increase by up to 643% & 784% (southern) under the combined C&SED(L/H) extreme scenario and by 432% & 282% (western) under the combined C&SED(L/L) extreme scenario. Similarly in eastern and northern Europe, the highest increases in the 75th and 95th percentile distributions are estimated at 553% (75th) and 642% (95th) under C&SED(L/H) scenario, and 643% (75th) and 485% (95th) under C&SED(L/L) scenario. These changes reflect that about 25% of the grid cells in each region experience an average of more than 350% increase in WEI under the low climate extreme scenarios, indicating the wide spread nature of water stress related issues across Europe.

Biodiversity vulnerability index

The BVI also generally increases under all the extreme socio-economic scenarios and upper bound extreme climate scenarios across most parts of the regions (Figure 6.24). However, the results show that the upper boundary extreme climate scenario also lead to some local improvement in BVI across most regions (except southern Europe), as indicated by the 5th percentile coverage with negative values (up to BVI=-1, showing availability of appropriate climate and/or habitat space for all the species). In southern Europe, there is an overall increase in BVI under all extreme scenarios, except a small improvement in vulnerability (i.e., BVI=-0.2) in some grid cells (<5%) under the CD(L) and C&SED(L/H) extreme scenarios. Unlike other regions, in western Europe in addition to the upper bound climate scenarios, the SED(L) extreme scenario also leads to a small improvement in vulnerability (with BVI=-0.3) locally, reflecting the positive indirect effect of some extreme socio-economic drivers in improving availability of appropriate habitat space for some species (particularly arable related species) in the region.

6.6 MDAT Scenario Implausibility Analysis

Figure 6.25 presents a summary of the percentile distributions of the European scale percentage changes (from baseline) of the various cross-sectoral impact indicators when considering the 'full ranges' of the various MDAT scenarios investigated in the sensitivity analysis (as presented and discussed in the preceding sections of this chapter).

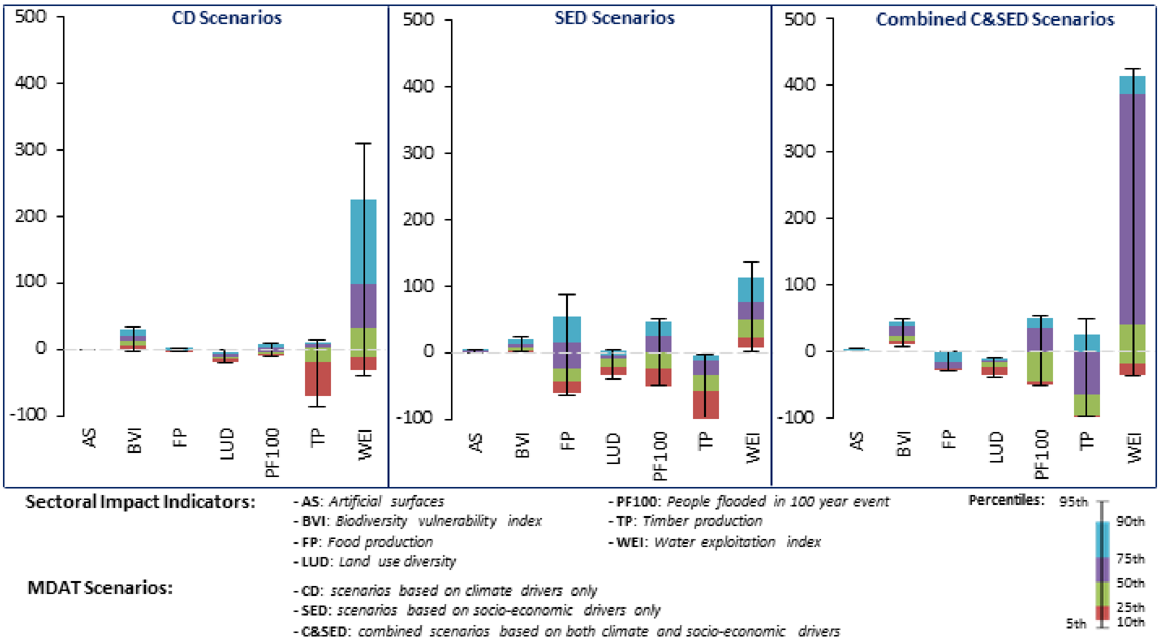


Figure 6.25: *A summary of percentile distributions of the Europe-wide % change (from baseline) of the impact indicators under the 'full range' of the MDAT scenarios investigated (see Figure 4.5 for details on the scenarios).*

Following the implausibility analysis approach presented in Section 4.5.3, this section presents how many of the MDAT climate and socio-economic scenarios could be identified as 'not-implausible' so that they can be used in the uncertainty analysis and ensemble-based simulations of the potential future cross-sectoral impact projections across Europe. The approach considers two criteria for identifying the plausible scenarios based on: (i) ranges identified from a review of the literature on future projections of the changes in the indicators investigated (see Section 4.5.3) and (ii) the ranges 10^{th} and 90^{th} percentiles of the estimates investigated based on the full ranges of the MDAT scenarios (this is added for comparison purposes). Table 6.4 presents a summary of the number of MDAT scenarios that are identified as 'not-implausible' based on the above two criteria. The summary shows that, compared to the $10^{th}/90^{th}$ percentile-based ranges, the literature-based plausible ranges are relatively narrow for SED scenarios (with only 13% of the total MDAT scenarios identified as 'not-implausible'), while it is wider for the CD scenarios (with 70% of the MDAT scenarios identified as 'not-implausible').

Table 6.4: *The number of 'not-implausible' scenarios selected from the 'full ranges' of the MDAT scenarios investigated based on projected ranges identified from the literature (Figure 4.6).*

Scenario Classes	Total no. of MDAT Scenarios Analysed	No. of 'not-implausible' scenarios selected from the full scenario ranges based on:			
		Literature (Section 4.5.3)		10th/90th %tile of the full scenario ranges*	
		No. of Scenarios	% relative to total	No. of Scenarios	% relative to total
CD Scenarios	1199	838	69.9	454	37.9
SED scenarios	599	77	12.9	222	37.1
C&SED Scenarios	8	1	12.5	2	25.0

*This is included for comparison purposes.

The analysis shows that when excluding the extremes outside the ranges between the 10th and 90th percentiles of the MDAT scenario distributions, only 38% of the climate and 37% of the socio-economic change scenarios could be considered 'plausible' across all the indicators (see Table 6.3). Focussing on these ranges, the results highlight that under the CD scenarios, the % change (from baseline) of the indicators are estimated as: 0.5 to 28.4% (BVI), -3.6 to 0.1% (FP), -19.7 to -4.2% (LUD), -9.7 to 7.7% (PF100), -70.9 to 9.9% (TP), and -32.5 to 224.8% (WEI). In contrast, under the SED scenarios the % changes are estimated as: 0 to 3.0% (AS), 1.0 to 19.1% (BVI), -62.0 to 55.2% (FP), -33.9 to 0.7% (LUD), -50.1 to 47.1% (PF100), -100 to -4.2% (TP), and 8.6 to 113.6% (WEI). When considering the 50th percentile distribution, the % changes in the indicators from the baseline estimated as mean$\pm$SD across the three scenario classes are: 0.5$\pm$0.8% (AS), 14.0$\pm$7.4% (BVI), -17.9$\pm$13.8% (FP), -12.6$\pm$3.8% (LUD), -1.8$\pm$1.8% (PF100), -31.8$\pm$34.4% (TP), and 41.0$\pm$8.4% (WEI) (Figure 6.25). However, when the literature-based scenario ranges are considered, these projections vary, especially for some sectors/sub-systems. Hence, focussing on those MDAT scenarios that are identified as 'not-implausible' based on the literature-based ranges (Table 6.4), the following sections present plausible projections of the potential uncertainties and ensemble-based simulations of future cross-sectoral impacts across Europe.

6.7 Uncertainty and Ensemble Projections of Impacts under Climate Scenarios

The implications of uncertainty in climate change (considering changes in temperature, precipitation, and CO_2 concentration combined with baseline socio-economic settings) and uncertainty in socio-economic factors (considering changes population, GDP, agricultural yields, and food imports, combined with baseline climate settings) on the magnitude and direction of changes and the spatial distribution of the cross-sectoral impacts and associated uncertainties are investigated based on simulations of: (i) the ensemble-based % changes (relative to baseline) in area-aggregate estimates of the sectoral indicators (i.e., % future changes in the area-average AS, BVI, LUD and WEI and area-total FP, PF100 and TP) (Sections 6.7.1 and 6.8.1) and (ii) the spatial distribution of the % changes (relative to baseline) in grid-based indicator values across Europe and the four regions (Sections 6.7.2 and 6.8.2) under the various 'not-implausible' climate and socio-economic scenarios. The results show significant spatial diversity in terms of the potential cross-sectoral impacts, and increasing uncertainty in the magnitude and direction of changes in the indicators from the European to regional scales associated with future climate and socio-economic change uncertainties, as discussed in more detail in the following sub-sections.

6.7.1 European and regional aggregate cross-sectoral impacts

Figure 6.26 presents uncertainties of the sectoral indicators focussing on the ensemble mean % change (from baseline) (with ± one standard deviation, SD) of the area-aggregated estimates across the 'not-implausible' climate scenarios. The results show that at the European scale, WEI shows the highest ensemble-mean change from baseline, projected with more than 17% increase in WEI, highlighting a high increase in potential Europe-wide issues of water stress. It is followed by a 13% average decline in LUD and 11% average increase in BVI, while TP is projected with an increase by less than 3%. In contrast, FP and PF100 show the least ensemble-mean change from baseline across the scenarios, which are projected with less than 2% decline (in FP) and just 0.1% increase (in PF100).

When considering the uncertainty ranges based on SD of the Europe-wide aggregate projections across the scenarios, WEI is still with the highest uncertainty, projected between -27% & +62% (Figure 6.26). The large increase is mainly attributed to the high-end scenarios that lead to higher decline in precipitation and increase in temperature, affecting both the supply side as well as the demand side (e.g., for irrigation water in some areas). Then, TP and BVI follow with a relatively moderate uncertainty ranges between -8% & +13% and -2% & +20%, respectively. In contrast, PF100 and LUD show a relatively small ensemble-based uncertainty at the European scale, with SD of just 6% and 5%, respectively. However, FP shows the least variation (from baseline), projected with just 2% SD. Although there are some regional variations (discussed below), the small changes in both the ensemble mean and SD are associated with the autonomous adaptation considered based on productivity/profitability and prioritization of land for agriculture under the various climate scenarios in order to maintain the existing Europe-wide food demand (under unchanged socio-economic factors, the effects of which is discussed in Section 6.8). This priority in food production implemented within the CLIMSAVE IAP has important regional implications on other sectors/sub-systems that are affected by land use changes, as discussed below. Nonetheless, the European scale results broadly illustrate that, while there is high uncertainty in terms of the directions of the ensemble-based changes for all sectors/sub-systems (except LUD, which shows robust decline), in terms of the magnitudes of change, most sectors/sub-systems (except WEI, which is projected with high uncertainty) show a relatively small ensemble-mean change across the various climate change scenarios investigated.

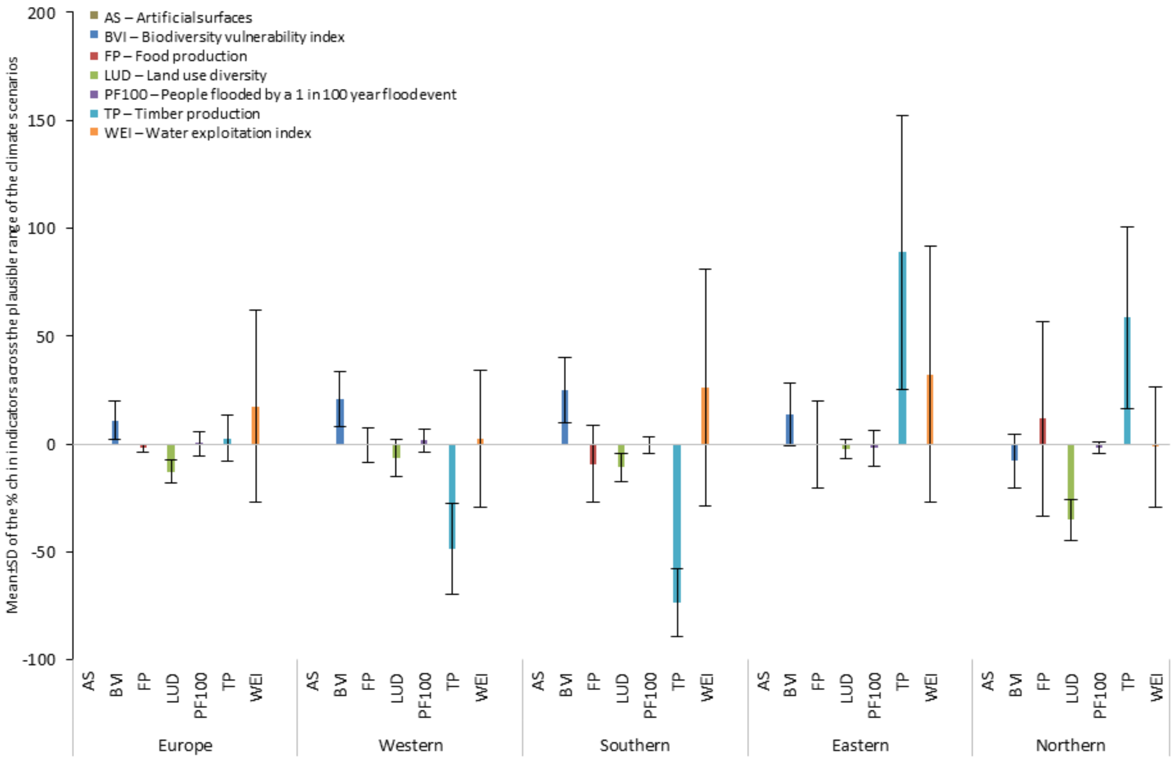


Figure 6.26: *Uncertainty of impacts due to climate change uncertainty summarised based on mean ±standard deviation (SD) of the % change in indicators from baseline for Europe and the four regions. Coloured boxes represent the ensemble mean % change across the 'not-implausible' range of CD scenarios, while error bars represent the ±SD from the mean. See Appendix C for the full ranges of MDAT CD scenarios.*

However, there are significant regional variations in terms of magnitude of the ensemble-mean changes as well as projected uncertainty ranges (both in magnitude and directions) across the indicators and regions. When considering the ensemble-average projections, except LUD (which declines in all regions), all other indicators show different directions of change across the regions, with varying magnitude of change. However, when comparing the magnitude of ensemble-mean % changes, TP shows the highest regional changes (from baseline), with varying magnitudes and directions of change across the regions. For example, the highest ensemble-based increase in TP is projected in eastern Europe, with a regional average estimate of 89%, followed by northern Europe with a mean change of 59%. In contrast, TP shows the highest average % decline in southern Europe (with more than 73% reduction) and western Europe (with a 49% decline). These are followed by WEI, particularly in eastern and southern Europe, with the ensemble-based averages estimates projected to increase (from baseline) by more than 32% and 26%, respectively. In contrast, the average changes in WEI in western and northern Europe are relatively small (i.e., +2.5% and -1.3%, respectively). Although with relatively small ensemble-based regional average % reductions (from baseline) in western and southern Europe (i.e., less than 7%), LUD is also projected with more than 35% decline in northern Europe. On the other hand, BVI projected to increase by 14–25% (from baseline) in eastern, western and southern Europe, while showing some (8%) improvement (reduction) in vulnerability in northern Europe. The high declines in LUD and BVI are associated with a north-ward shift of agriculture under most climate scenarios, dominating the land use (hence reducing diversity) and increasing habitat space (especially for arable-related species, resulting in a reduction in vulnerability). The ensemble-based regional average changes in FP are projected as +12% (northern), -9% (southern), and less than 0.6% decline in western and eastern Europe. In contrast, PF100 shows the least ensemble-based average changes across the regions (i.e., less than 2%).

When focussing on projections of uncertainties based on the SD, WEI shows the highest uncertainty, particularly in eastern and southern Europe, with the ensemble-based changes (from baseline) estimated between -32% & +127% and -33% & +112%, respectively. In contrast, the uncertainties in WEI for western and northern Europe are projected between -32% & +127% and -33% & +112%, respectively. However, the ensemble-based uncertainty ranges for TP are projected between +25% & +152% (eastern), +17% & +101% (northern), -70% & -28% (western), and -89% & -58% (southern Europe). For FP, the highest uncertainty is projected in northern Europe (i.e., from -33% to +57%), while ranging between ±20% (eastern), -27% & +9% (southern), and -9% & -8% (western Europe). In contrast, BVI shows medium uncertainty across the regions, with the ensemble-based projections ranging between +10% & +40% (southern), -1% & -28% (eastern), +8% & +34% (western), and -20% & +4% (northern Europe). However, LUD and PF100 generally show low uncertainty, with SD ranging between 5–10% (LUD) and 3–8% (PF100) across the regions under the various climate scenarios. The following sub-section presents the grid-based spatial distribution of the % changes (from baseline) across Europe focusing on the ensemble-mean and European low- and high-end scenarios.

6.7.2 Grid-based spatial distribution of cross-sectoral impacts across Europe

People flooded in a 1 in 100 year flood event

Figure 6.27 presents a spatial distribution of the % change in PF100 (per grid cell) under the two extreme scenarios as well as the ensemble mean considering the range of 'not-implausible' climate scenarios. Under these scenarios, while there are uncertainties in terms of the direction of changes in future impacts of flooding across most of Europe; northern Germany is identified as a potential hotspot with impacts increasing across all the scenarios investigated (including the two extreme scenarios; Figure 6.27a and c). In contrast, some places such as southern Sweden and north-western Italy show a decline in flood impacts under both the low and high end scenarios. When considering the ensemble mean simulation (across all the 'not-implausible' scenarios), although there is generally a decline in PF100 across Europe (especially in eastern Europe), there are significant local implications (with more than 50% increase in PF100 from the baseline) in some areas such as again in northern Germany as well as in southern Europe. However, under the high scenario, except in some areas, wide spread increase in potential flood impacts are also projected that are significant locally, mainly associated with the increase in precipitation (Figure 6.27c).

Figure 6.27: *Spatial distribution of the % change (from baseline) in the number of people flooded in Europe under the low (a), high (c), and ensemble mean simulations (b) across the 'not-implausible' ranges of climate change scenarios.*

Land use-related indicators: food production, timber production and land use diversity

Figure 6.28 presents the spatial distribution of the % change in FP across Europe under two extreme scenarios as well as the ensemble mean (across the 'not-implausible' ranges of scenarios). The results show that there is a robust increase in food production in places such as southern Finland and west Norway (in northern Europe), north-west of UK and Ireland (in western Europe), northern Romania and Slovakia (in Eastern Europe), and part of central

Europe across the scenarios investigated. In contrast, part of the Mediterranean region (such as southern France and northern Italy) and northern part of Scandinavia are identified as potential hotspots with food security issues in terms of declining agricultural productivity under most of the scenarios.

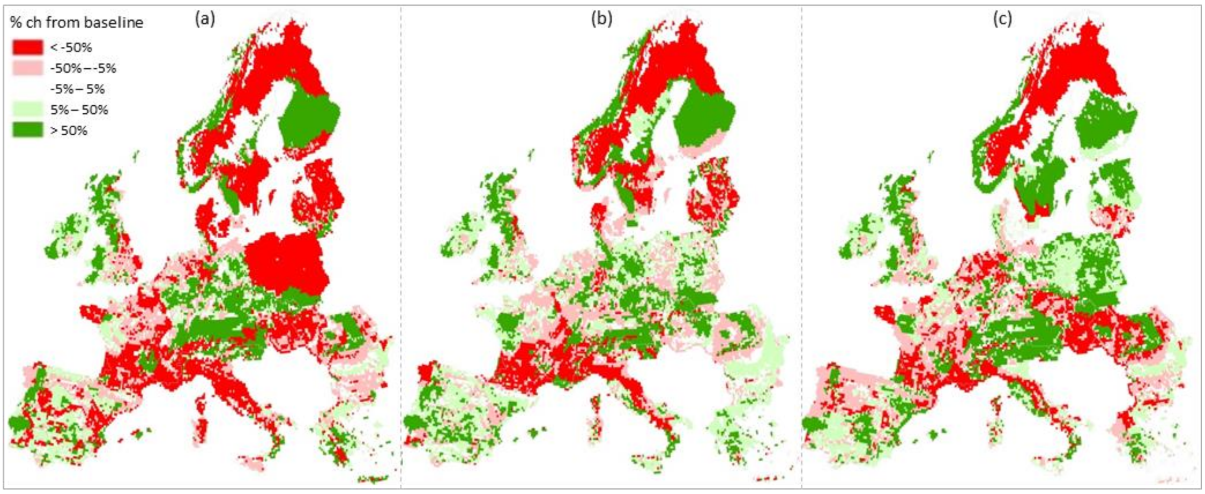


Figure 6.28: *Spatial distribution of the % change (from baseline) in food production in Europe under the low (a), high (c), and ensemble mean simulations (b) across the 'not-implausible' ranges of climate change scenarios.*

Figure 6.29 illustrates the spatial distribution of the projected TP under two extreme as well as ensemble mean simulations across the 'not-implausible' ranges of scenarios investigated. Under the low scenario, a loss of forest area is projected across the whole of Europe, resulting in a reduction in timber production across Europe (exceptions are Ireland, France, and to a lesser extent in parts of eastern European areas). This is mainly attributed to the increase in agricultural land use under the scenarios which make it difficult to produce more food with existing land (reduced productivity), leading to an expansion of, for example, intensive farming or grass land to meet existing food demand, at the expense of forestry. However, under the high scenario (with higher CO_2 levels, which makes it possible to produce more timber within small areas), there is a pronounced improvement in forest growth and productivity (e.g., in parts of northern and eastern Europe and north eastern Scotland), resulting in a significant increase in production. A similar spatial pattern is also projected under the ensemble mean simulation, with a robust decline in most parts of southern and western Europe, while increasing in northern and eastern Europe.

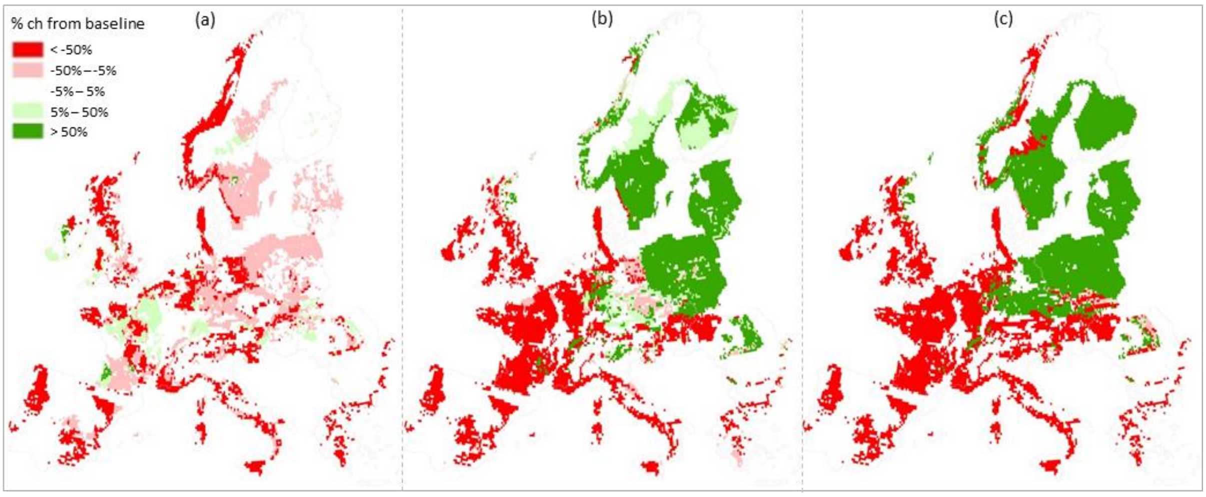


Figure 6.29: *Spatial distribution of the % change (from baseline) in timber production in Europe under the low (a), high (c), and ensemble mean simulations (b) across the 'not-implausible' ranges of climate change scenarios.*

Figure 6.30 presents the spatial distribution of the grid-based changes in land use diversity across Europe based on the two extreme and ensemble mean simulations of the 'not-implausible' scenario ranges. The results highlight that there are robust changes across the scenarios in some places, such as northern Sweden and parts of central Europe (with projected declines) and parts of Finland, Denmark, Greece and Portugal (with projected increases). Under the low scenario, there is a significant decline in land use diversity in most parts of Europe, particularly in southern, northern, and part of western Europe (Figure 6.30a). This is mainly associated with the expansion of agricultural land use in under the scenarios, dominating the land use (hence leading to a reduction in diversity). On the other hand, LUD is projected to increase in many places across Europe, except in northern Sweden and parts of central Europe (Figure 6.30c).

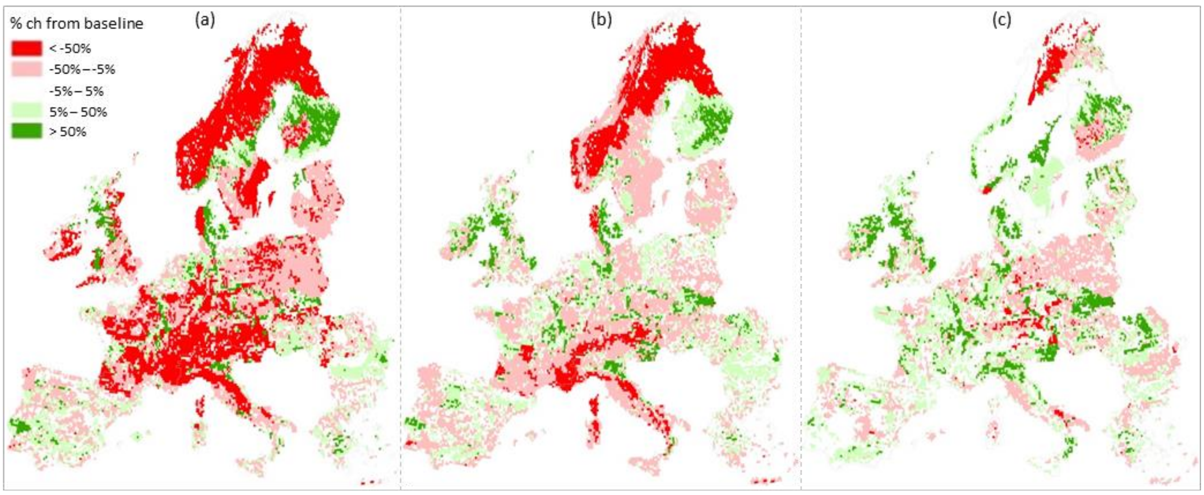


Figure 6.30: *Spatial distribution of the % change (from baseline) in land use diversity in Europe under the low (a), high (c), and ensemble mean simulations (b) across the 'not-implausible' ranges of climate change scenarios.*

Water exploitation index

Figure 6.31 illustrates the spatial variation of water stress problems across Europe under the two extreme scenarios (a and c) and ensemble mean simulations (b) across the various 'not-implausible' scenarios investigated. There is high uncertainty in future projections in water stress across Europe, with exceptions in parts of northern Portugal and Spain where there is robust increase in WEI across the scenarios. Under the low scenario, there is a relatively high improvement in water stress in southern Europe, relative to current condition (Figure 6.31a). In contrast, a significant increase in WEI is projected under the high scenario across whole of Europe (except in Norway and northern UK), highlighting the potential wide-spread nature of future water stress related issues across Europe (Figure 6.31c). Even under the ensemble simulation, WEI is projected to increase across most part of Europe, except southern Spain (Figure 6.31b). The highest increase is projected in parts of southern Europe (such as Spain, southern France and Italy) and eastern Europe (such as Romania, Poland and Bulgaria).

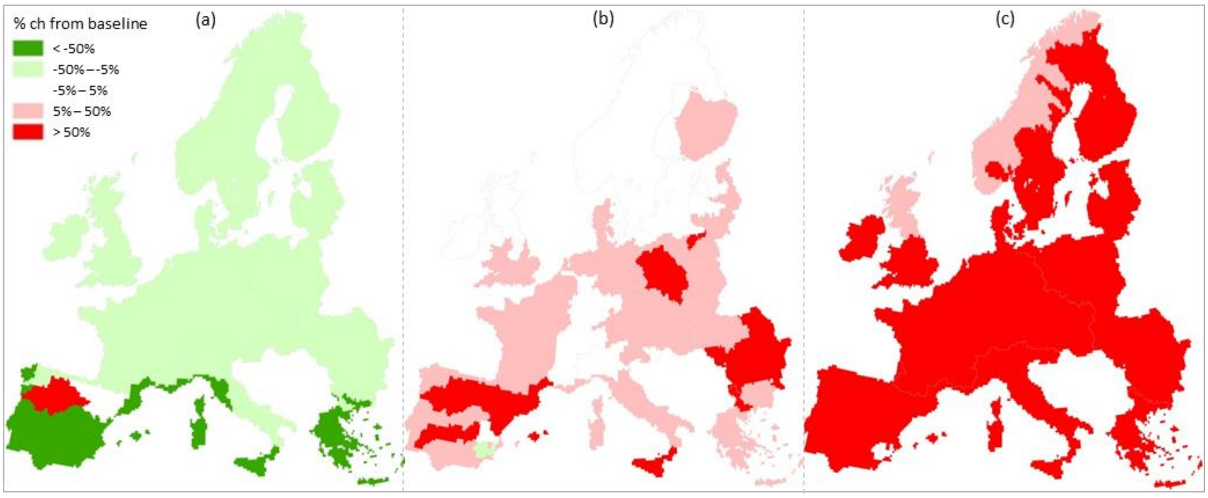


Figure 6.31: *Spatial distribution of the % change (from baseline) in water exploitation index in Europe under the low (a), high (c), and ensemble mean simulations (b) across the 'not-implausible' ranges of climate change scenarios.*

Biodiversity vulnerability index

Figure 6.32 shows the spatial distribution of the grid-based percentage changes in BVI from baseline under two extreme scenarios (Figure 6.32a,c) and an ensemble mean simulation across all the not-implausible climate scenarios (Figure 6.32b). The results show that while uncertain in most places, there is robustness in terms of the directions of change in BVI in parts of northern Europe and Romania (with improvement in vulnerability) and in north western Denmark and Lithuania, (with increased vulnerability) across the scenarios. Under the low scenario, significant biodiversity improvement is projected across Europe (with an overall decline in BVI of 13%). This is particularly the case in northern (e.g., southern Norway, Sweden and Finland), southern (e.g., Spain), and eastern (e.g., in Poland and Romania) Europe (Figure 6.32a).

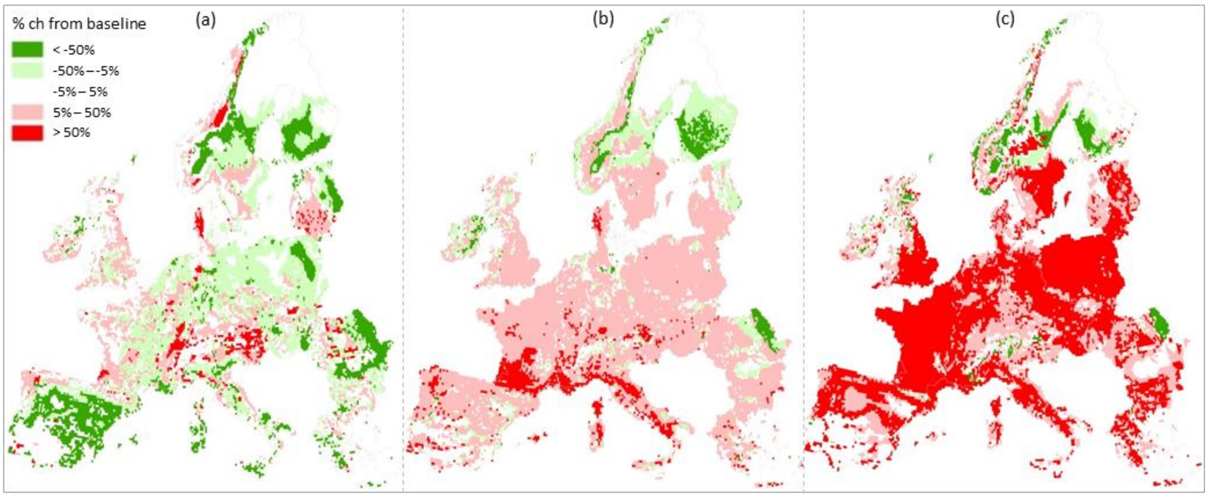


Figure 6.32: *Spatial distribution of the % change (from baseline) in biodiversity vulnerability index in Europe under the low (a), high (c), and ensemble mean simulations (b) across the 'not-implausible' ranges of climate change scenarios.*

6.8 Uncertainty and Ensemble Projections of Impacts under Socio-Economic Scenarios

6.8.1 European and regional aggregate cross-sectoral impacts

Figure 6.33 presents area-aggregate summary of uncertainties of the indicators based on the ensemble mean (± one standard deviation, SD) % change (from baseline) across the 'not-implausible' socio-economic scenarios. The results show that at the European scale, although there are significant variations in terms of the magnitudes of change, there is an overall agreement (robustness) in terms of the directions of change (from baseline) in all (except FP and PF100) sectors/sub-systems: WEI, BVI and AS show increase-only trend, while LUD and TP show decline-only trend across all the socio-economic scenarios. At the regional scale, while there are agreements in the directions of change in some sectors/sub-systems, there is high uncertainty in most sectors/sub-systems both in terms of the directions as well as magnitudes of change from baseline. For example, although relatively small in magnitude, both AS and BVI show robust (increase-only) changes across all the scenarios in all regions. Similarly, FP (in southern Europe) and WEI (in all except northern Europe) show robust (increase-only) changes across the scenarios. In contrast, LUD (in northern Europe) and TP (in western and southern Europe) show decline-only (robust) changes across the scenarios.

When considering magnitudes of the ensemble-based projections of the average % changes (from baseline), there is high uncertainty in most sectors/sub-systems and regions across the scenarios. At the European scale, WEI identified with the highest average % change from baseline, projected with a 42% increase from baseline. This is significantly higher than the changes in all other indicators, which are projected with less than 10% average change (ranging between +0.8% in FP and +10% in PF/-10% in LUD). However, when considering the uncertainty ranges based on Mean±SD, WEI and FP are projected with the highest uncertainty across the socio-economic scenarios, ranging between +20% & +63% (WEI) and -18% & +20% (FP). Then, PF and LUD follow with uncertainty ranges of 24% (i.e., between -3% & +22%) and 12% (i.e., between -16% & +4%), respectively. In contrast, AS, BVI and TP are projected with low uncertainty: their ranges in the % change from baseline estimated at less than 7%.

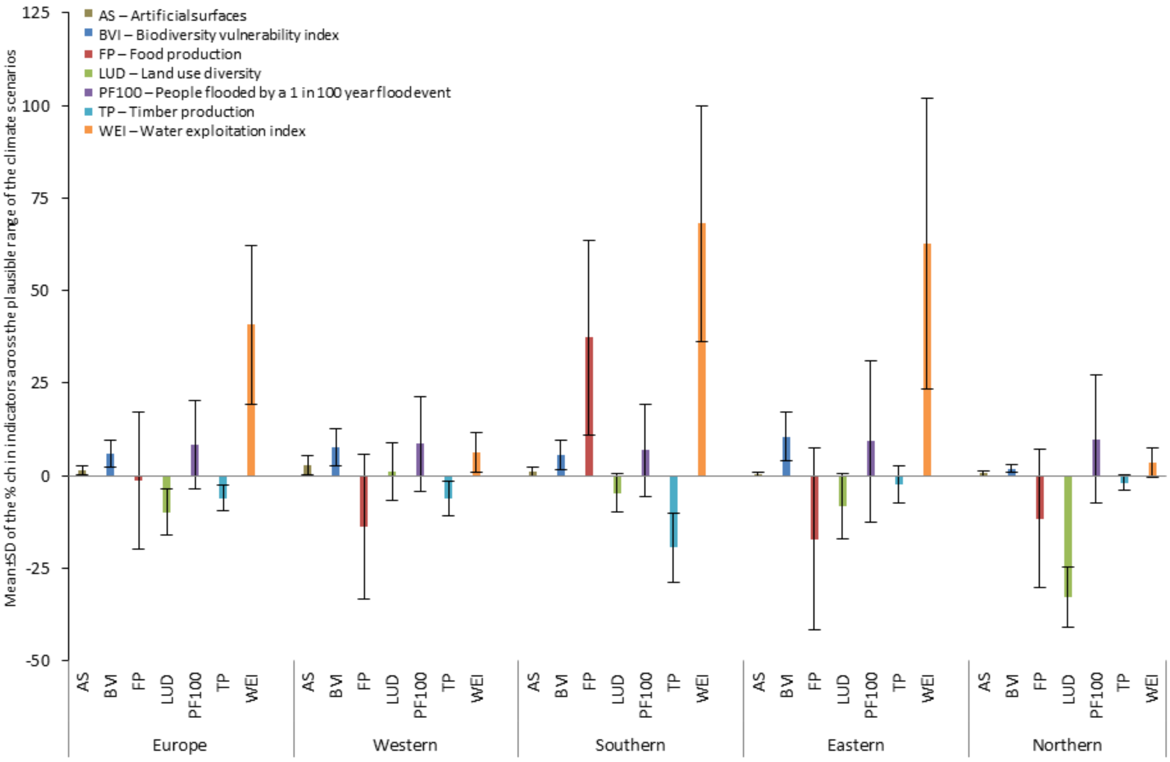


Figure 6.33: *Uncertainty of impacts due to socio-economic change uncertainty summarised based on mean ±standard deviation (SD) of the % change in indicators from baseline for Europe and the four regions. Coloured boxes represent the ensemble mean % change across all the 'not-implausible' range of SED scenarios, while error bars represent the ±SD from the mean.*

At the regional scale, while relatively small in western Europe, the highest relative changes in most of the indicators occur in southern and eastern Europe. In magnitude terms, the highest ensemble-based average % change (from baseline) is projected for WEI in southern and eastern Europe, increasing by more than 70% and 63%, respectively, across the various socio-economic scenarios. In contrast, % changes of WEI in western and northern Europe are relatively small (projected with less than 7%). also increases by 12% (which is also the highest increase in the region than other sectors/sub-systems) and 6% in western and northern Europe, respectively. However, FP in southern Europe is projected with the second highest average % change, increasing from baseline by more than 40%, while projected to decline by 9% and 12%

in northern and western Europe, respectively. In contrast, LUD (northern), TP (southern), and FP (eastern Europe) are projected with the highest decline from baseline, which are estimated at 33%, 20%, and 15%, respectively. On the other hand, PF100 is projected with an average of just 9–12% increase (from baseline) across the four regions. Similarly, the average % changes in BVI are projected in the range between +2% (northern) and 12% (eastern Europe). AS shows the least relative change (from baseline), with the highest average % increase estimated at just 3% in western Europe.

When considering uncertainties based on SD of the projections, again WEI is identified with the highest uncertainty, particularly in southern and eastern Europe, with the uncertainty ranges estimated between +38% & +102% and +24% & +103%, respectively. In contrast, in western and northern Europe the uncertainty in WEI is very small, projected between +1% & +12% and -1% & +7%, respectively. On the other hand, the uncertainty ranges for FP are projected between +14% & +67% (southern), -40% & +10% (eastern), -32% & +8% (western), and -29% & +10% (northern Europe). Similarly, the uncertainty ranges for PF100 are projected between -12% & +32% (eastern), -6% & +29% (northern), -4% & +23% (western), and -4% & +22% (southern Europe). For TP, the highest uncertainty is projected in southern Europe (with a range between -29% & +10%), while 2*SD estimated less than 10% in the other regions. In contrast, 2*SD for LUD, BVI and AS, respectively, are projected in the range between 10–18%, 2–13%, and 1–5% across the regions, reflecting the relatively small ranges of uncertainty across the various socio-economic scenarios. The following sub-section presents the grid-based spatial distribution of the % changes (from baseline) across Europe focusing on the ensemble-mean and European low- and high-end scenarios.

6.8.2 Grid-based spatial distribution of cross-sectoral impacts across Europe

Artificial surfaces

Figure 34 shows the extreme and ensemble-based simulations of the spatial distribution of the grid-based changes in artificial surfaces under the selected not-implausible scenarios. The results show that there is a robust change (increase-only) in urban areas across the scenarios. However, in terms of the magnitudes of change, there are only less than 5% grid-based changes in AS from baseline under the low scenario (Figure 34a). In contrast, there is a wide spread medium (5-50%) increase in AS across Europe, particularly in western and parts of southern Europe, except in Belgium with more than 50% increase in AS in some areas (Figure 34c). The results also show a particular concentration of growth in AS in coastal areas, with important implications on future risk of flooding associated with increase in people living within floodplains. Similarly, under the ensemble-based simulation, there is a concentration of urban growth in western Europe, particularly in Belgium, the Netherland, and the UK (Figure 34b).

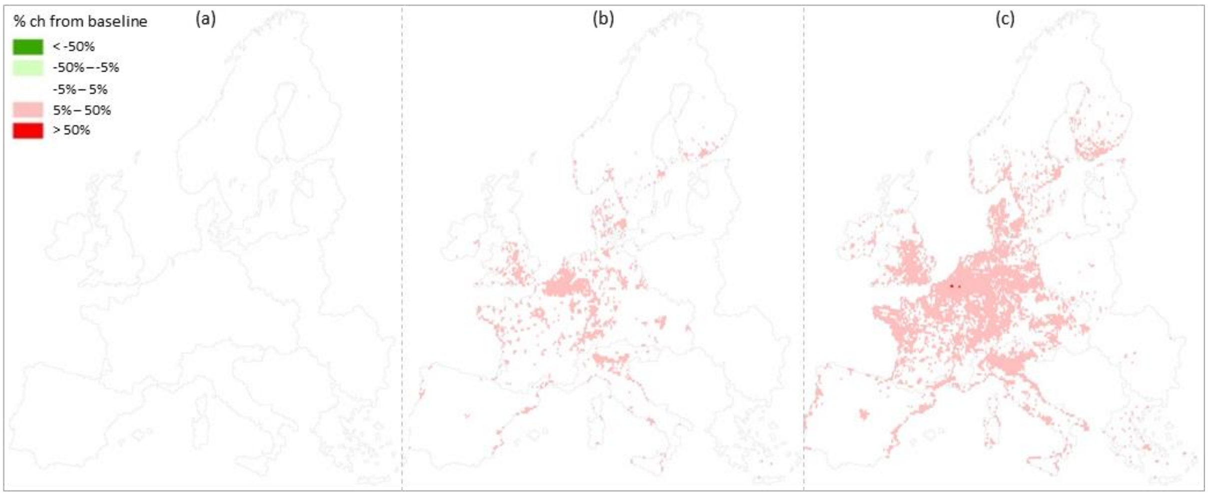


Figure 6.34: *Spatial distribution of the % change (from baseline) in artificial surfaces in Europe under the low (a), high (c), and ensemble mean simulations (b) across the 'not-implausible' ranges of socio-economic change scenarios.*

People flooded in a 1 in 100 year flood event

Figure 35 presents a spatial distribution of the % change in AS (per grid cell) under two extreme scenarios as well as the ensemble mean simulation considering the range of 'not-implausible' socio-economic scenarios. Under these scenarios, there is robust change (increase) in future impacts of flooding across Europe across the scenarios, mainly associated with the increase in population under both extreme scenarios. Under the low scenarios, the changes are high in western and parts of southern Europe, such as areas in Germany, France, United Kingdom, and Italy (Figure 35a). Under the high scenario, there is a significant increase in potential flood impacts in eastern Europe, as well as parts of southern Europe (e.g., southern France) (Figure 35c). Under the ensemble-mean simulation, although less in magnitude (i.e., 5 to 50%) there is a similar spatial distribution of potential flood impacts across Europe, with some areas in Romania, Poland and Lithuania projected with more than 50% increase (Figure 35b). This is mainly associated with the scenarios with population increase, including in floodplains. However, future changes in flood impacts are relatively small in northern Europe across the scenarios.

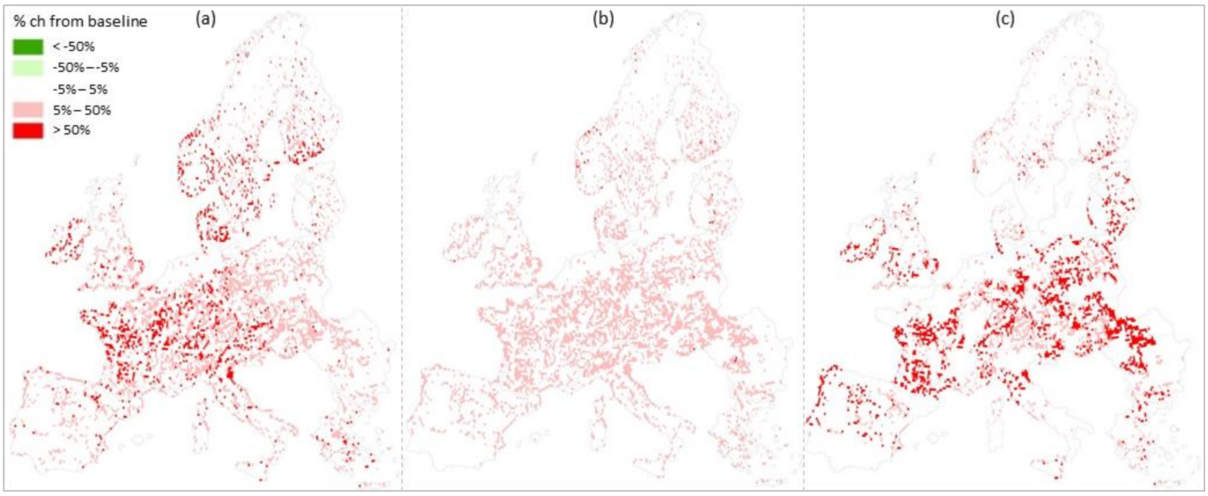


Figure 6.35: *Spatial distribution of the % change (from baseline) in the number of people flooded in Europe under the low (a), high (c), and ensemble mean simulations (b) across the 'not-implausible' ranges of socio-economic change scenarios.*

Land use-related indicators: food production, timber production and land use diversity

Similarly, Figure 36 presents the spatial distribution of the % change in FP across Europe under the two extreme scenarios and the ensemble mean simulation (across the 'not-implausible' ranges of scenarios). The results show that there is robustness in the directions of future changes in food production in some regions across the scenarios. For example, large parts of northern and some parts of central Europe are projected with a decline in production. On the other hand, parts of southern and south eastern Europe are projected with an increase in future production across the scenarios. The low scenario represents an increase in food imports, agricultural yield and GDP combined with current population, leading to a wide spread decline in food production associated with less demand for production across most parts Europe (Figure 36a). However, under the high scenario associated with an increase in population (hence demand) without food import and decline in GDP, leading to an increase in production to meet demand. Under unchanged climate, high productive areas will be to produce more, as reflected in the significant increase in FP in western, southern, and eastern Europe (Figure 36c). Similarly, with unchanged climate conditions and depending on the uncertainties in future changes in socio-economic factors, the ensemble-based simulations show that future food production is projected to increase in southern (such as Portugal, Spain, Italy) and eastern (such as Romania and Bulgaria), and parts of southern (e.g., France and United Kingdom) Europe. In contrast, northern and north-eastern Europe will experience a significant reduction in food production (Figure 36b).

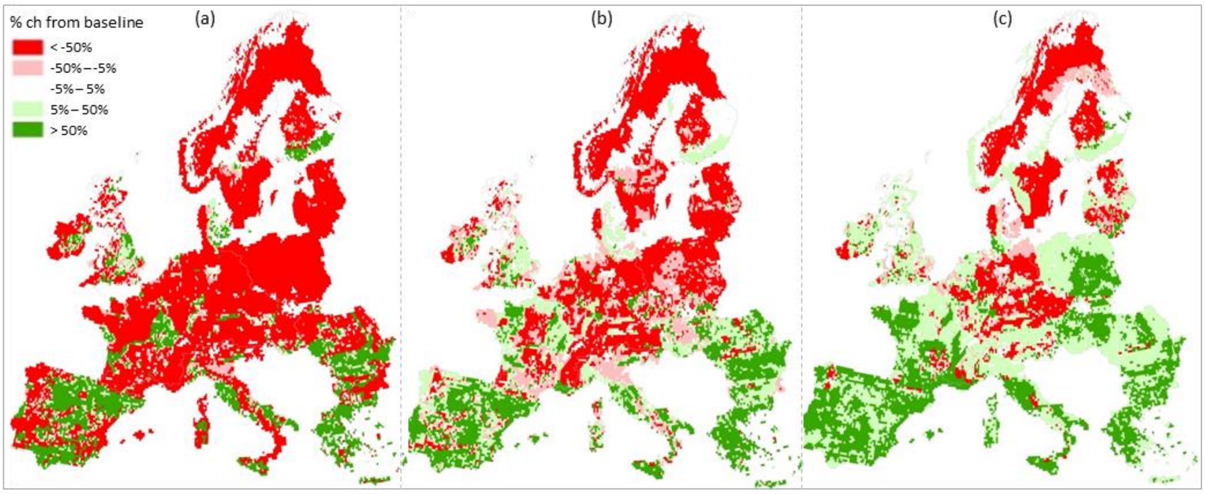


Figure 6.36: *Spatial distribution of the % change (from baseline) in food production in Europe under the low (a), high (c), and ensemble mean simulations (b) across the 'not-implausible' ranges of socio-economic change scenarios.*

Figure 37 illustrates the spatial distribution of the projected TP under the two extreme scenarios and ensemble mean simulations across the 'not-implausible' ranges investigated. Under the low scenario, there is an overall decline in timber production across Europe. This is particularly significant in some areas such as southern France, Germany, Czech Republic, central Spain and northern Portugal, Lithuania and southern Sweden (Figure 37a). In contrast, under the high scenario, although small changes in most places across Europe, there are high increase in timber production in some places, such as Poland, France, north-eastern Germany, Hungary. However, a significant decline is projected in central Spain, possibly due to low productivity of the land for forestry than agricultural use Figure 37c. When the ensemble mean simulations are considered, a significant reduction (more than 50% per grid) in production is projected in southern Europe, such as Spain, Italy, Greece, and Portugal. In addition, while there is a moderate (5-50% per grid) decline in TP across most parts of Europe, an in increase in TP (by over 5%) is also projected in some places such as Poland, north Germany, Sweden, Ireland, etc. (Figure 37b).

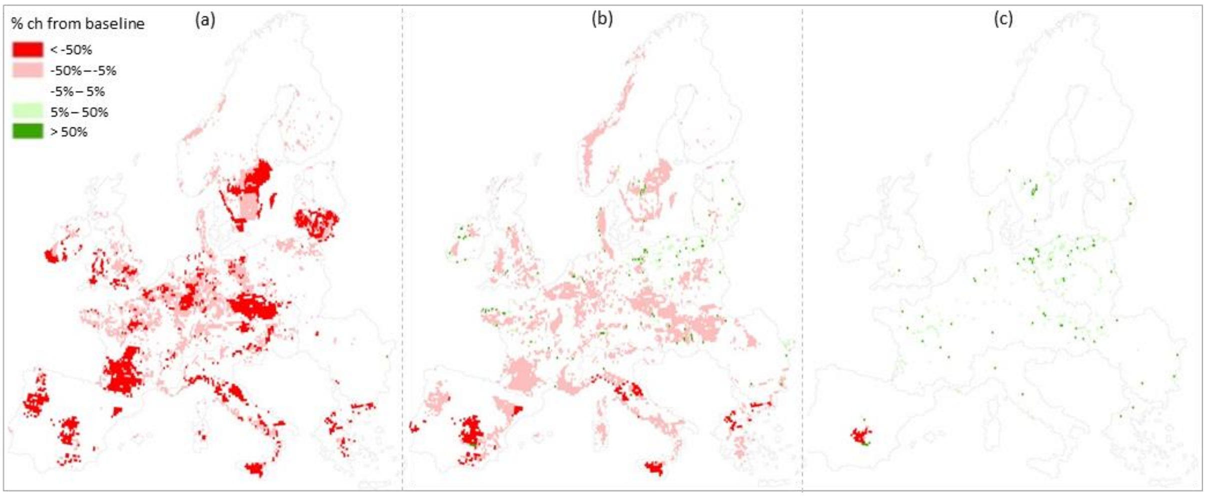


Figure 6.37: *Spatial distribution of the % change (from baseline) in timber production in Europe under the low (a), high (c), and ensemble mean simulations (b) across the 'not-implausible' ranges of socio-economic change scenarios.*

Figure 38 presents the spatial distribution of the grid-based changes in land use diversity across Europe based on the two extreme and ensemble mean simulations of the 'not-implausible' scenario ranges. The results highlight that while there is robust changes across the scenarios in some places, such as southern Sweden and southern Finland, there is a significant uncertainty in the directions of change in LUD across Europe under the range of scenarios. Under the low scenario, there is a significant decline in land use diversity in most parts of Europe, particularly in northern, western Europe and parts of southern Europe (e.g., Italy), while increasing in other places such as the UK, Ireland, France, northern Italy, Greece and Romania (Figure 38a). In contrast, under the high scenario, the changes are relatively small across most part of Europe except in areas such as central northern France Romania and Czech Rep (with high decrease) and Ireland, Demark, Slovakia and Romania (with high increase). However, when the ensemble mean simulations are considered, a significant decline in LUD is projected in northern Europe (such as Norway, and northern Sweden and Finland) as well as western Europe (e.g., eastern France, Switzerland and Austria). This partly reflects the northward shift of agriculture as a dominant land use under the scenarios, resulting in a reduction in diversity. On the other hand, northern Italy, most parts of western Europe countries as well as parts of Romania are projected with a significant increase in land use diversity (Figure 38b).

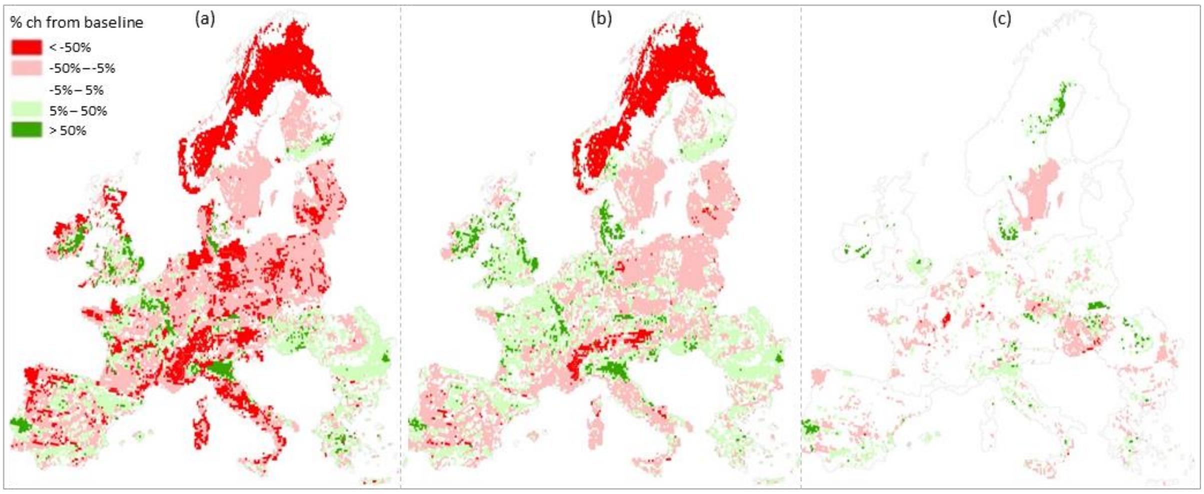


Figure 6.38: *Spatial distribution of the % change (from baseline) in land use diversity in Europe under the low (a), high (c), and ensemble mean simulations (b) across the 'not-implausible' ranges of socio-economic change scenarios.*

Water exploitation index

Figure 39 illustrates the spatial variation of water stress problems in Europe under the two extreme scenarios (a and c) and ensemble mean simulations (b) across the various 'not-implausible' scenarios investigated. Under the low scenario, a moderate reduction in water stress is projected in southern Europe, except in southern Spain and Portugal (Figure 39a). This is mainly associated with the decline in irrigation water use under the scenario, which considers an increase in food imports under unchanged population (and hence less water demand for agriculture). However, both the high (Figure 39c) and ensemble mean simulation (Figure 39b) scenario projections show that there is a significant increase in issue of water stress in southern and south eastern Europe. For example, the high extreme scenario represents a reduction in food imports combined with an increase in GDP resulting in, for example, increased demand for irrigation water (in the south, hence adding pressure on water resources) as well as increased demand for domestic water use (in eastern Europe, e.g., due to increased use of water appliances as GDP per capita grows). In contrast, relatively small (<5%) changes in water exploitation index is projected in northern Europe.

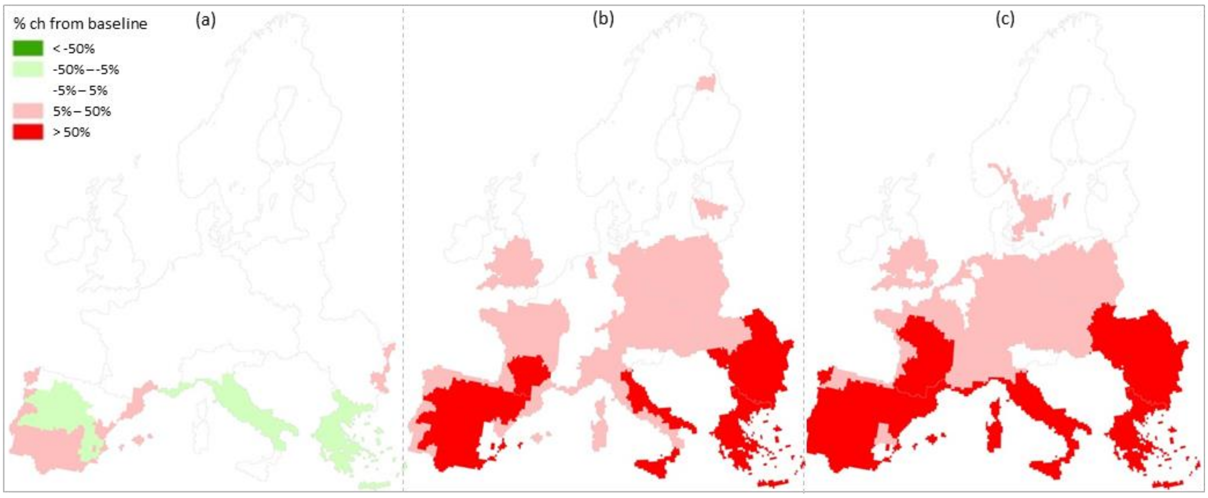


Figure 6.39: *Spatial distribution of the % change (from baseline) in water exploitation index in Europe under the low (a), high (c), and ensemble mean simulations (b) across the 'not-implausible' ranges of socio-economic change scenarios.*

Biodiversity vulnerability index

Figure 40 shows the spatial distribution of the percentage change in grid cell value of BVI from baseline under the two extreme scenarios (a & c) and an ensemble mean across all not-implausible scenarios (c). Under the low scenario, the results show that unlike the climate change scenarios, the effect of changes in the socio-economic factors are relatively small, with <5% per grid change from baseline across most parts of Europe, except some areas in Greece, along the east coast of Spain, Ireland and in some eastern Europe countries (projected with moderate to high increase in BVI) (Figure 40a). This is mainly associated with the relatively small change in agricultural land use under the scenario, which represents a 25% population growth as well as a 20% increase in food imports (hence maintaining food demand). However, under the high scenario, a wide spread biodiversity vulnerability is projected, particularly in central part of Europe, and southern and south eastern European regions (Figure 40b). In addition, when the ensemble-mean simulations are considered mostly moderate grid-based increase in biodiversity vulnerability is projected across Europe. However, significant increases in grid-based BVI are also projected in some countries such as Austria, northern Germany southern Portugal, and south-eastern Spain and France and northern Lithuania. In contrast, mostly moderate improvement in vulnerability is also projected in some eastern countries as well as in Ireland, southern Portugal, eastern Spain and southern France (Figure 40b). These results broadly highlight the potential implications of land use change due to socio-economic changes.

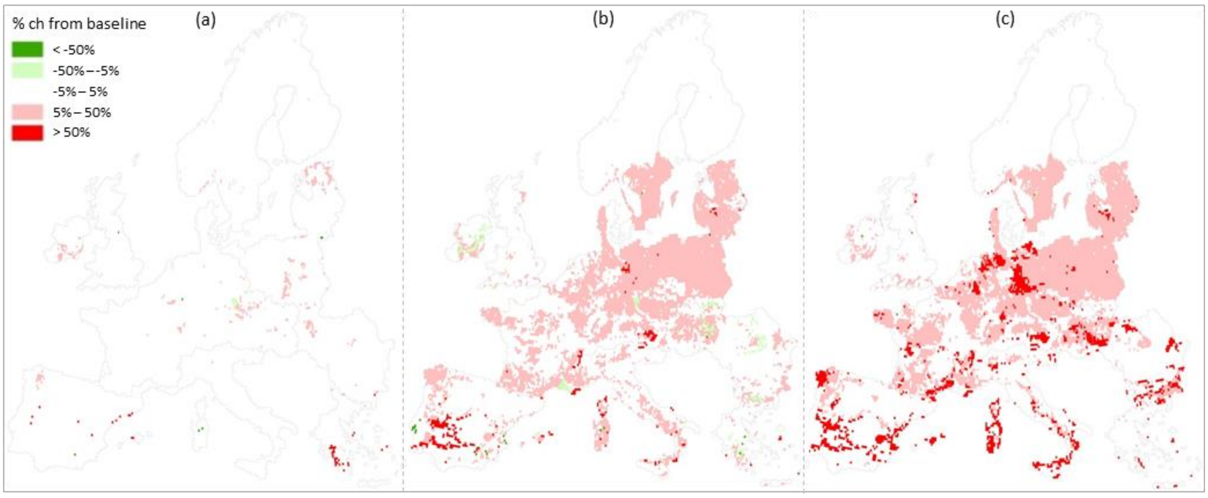


Figure 6.40: *Spatial distribution of the % change (from baseline) in biodiversity vulnerability index in Europe under the low (a), high (c), and ensemble mean simulations (b) across the 'not-implausible' ranges of socio-economic change scenarios.*

7. THE ROLE OF IAMs IN UNDERSTANDING THE FOOD-WATER-LAND-ECOSYSTEMS NEXUS

7.1 Introduction

The human and natural systems interact at different scales in space and time, and future changes in climate and socio-economic conditions will have important implications on the sustainability of resources supporting these systems. Misselhorn *et al*. (2012) argued that multi-disciplinary, cross-sectoral and cross-scale integrated approaches to decision-making are at the centre of the concept of sustainability. Understanding these complex interactions plays an important role in designing robust policy measures for a sustainable and climate-resilient management of future impacts across sectors/sub-systems, scales, and future climate and socio-economic scenarios. In addition, these interactions and responses are often non-linear, which increases the challenge in predicting future impacts across sectors/sub-systems and scales as well as the possible adaptation required to reduce and/or offset potential vulnerabilities. Liu *et al*. (2015) suggested that "Systems integration – holistic approaches to integrating various components of coupled human and natural systems – is critical to understand socio-economic and environmental interconnections and to create sustainability solutions" (p.964).

Whilst a number of integrated frameworks and assessment models have been developed and applied under a range of disciplines, scales, and complexities, there are still some key limitations/potential required improvements, and challenges still remain particularly in terms of informing local to regional adaptation decision-making across sectors/sub-systems and scales (see Serrao-Neumann *et al*. 2014). This chapter presents an introduction of the current knowledge on systems integration, and discusses the findings of an integrated assessment of the potential implications of future climate and socio-economic changes on the European food-water-land-ecosystems (FWEL) nexus and associated cross-sectoral synergies, conflicts and trade-offs. This is followed by identifying the key features and potential improvements of the CLIMSAVE IAP specifically, and IAMs more generally. Finally, the road ahead in terms of the future directions in informing development of the next generation of IAMs is outlined.

7.2 Cross-Sectoral Systems Integration: The Food-Water-Land-Ecosystems Nexus

Food, water and land are the most precious resources that are needed as vital life support systems for human well-being and health of the natural ecosystems (Netafim 2013). Future projections indicate that demand for food and freshwater will increase significantly over the coming decades associated with the increasing pressure of climate change as well as future economic development, population growth and mobility, diversifying diets, and technological and policy changes (Hoff 2011). For example, globally agriculture accounts for 70% of total freshwater withdrawals, and future agricultural policies play an important driving role for land use structure and landscape quality (van Delden *et al*. 2010). Land use change is also considered as one of the most important processes and drivers of global change (Schaldach and Priess 2008). Hence, the areas of land, water, food and environmental policies within the context of climate change have numerous interwoven concerns ranging from access to services to various environmental implications and future adaptation challenges (Bazilian *et al*. 2011). These issues materialize in various ways in each of the four sectoral directions, but often the key impacts are closely inter-related as highlighted in previous chapters. As demand grows due to changing conditions, the increasing competition for these resources and other sectors/sub-systems is highly dependent on the complex interactions and feedbacks between the sectors/sub-systems (see Chapters 5 and 6). The research highlighted that the various interdependencies between the six key sectors/sub-systems in Europe will have important implications on the long-term use and management of these finite natural resources. Hence, within the context of future climatic and socio-economic changes, understanding the food-water-land-ecosystems (FWLE) nexus *a-priori* plays an important role to systematically analyze the complex interactions between the various human activities and the natural environment (Bazilian *et al*. 2011). This is central for making informed plans and policy choices for long-term adaptation and mitigation responses required to address future issues of sustainability and climate-resilience challenges in terms of food security, water stress, loss of biodiversity, and potential risks of environmental hazards (e.g., flooding). As such, the nexus conceptual approach provides a cross-sectoral and dynamic perspective of future impacts for a more integrated management and use of resources through a cost-effective planning, decision-making, implementation, monitoring and evaluation of possible response measures by identifying and managing trade-offs to build synergies and reduce unintended conflicts (FAO 2014).

The CLIMSAVE framework and its IAP provided, as a first European level initiative, such systems integration-based modelling approach for quantifying cross-sectoral impacts of and adaptation to both climate and socio-economic changes considering the nexus between various sectors/sub-systems. As such, the integrated methodology used takes into account important linkages and interactions between six key land- and water-based environmental and resources sectors/sub-systems and various adaptation measures by integrating more than ten disparate sectoral meta-models within a common platform. The various meta-models involved were satisfactorily validated independently against baseline data and/or the validated outputs of the original more complex models from which the meta-models are developed (see Holman and Harrison (2012) for more details). The remaining sub-sections of the chapter discusses the key messages in terms of the three main aspects of the research focussing on: (i) the key sensitivities and uncertainties of the multi- and cross-sectoral impacts of and adaptation to future changes in climate as well as social, economic, environmental, technological, and policy governance in Europe focussing on the nexus between the six sectors/sub-systems based on application of the CLIMSAVE IAP; (ii) the overall lessons from CLIMSAVE's integrated methodology in terms of the key strengths in improving current integrated analysis and modelling approaches as well as current limitations and the potential for future improvements, and (iii) the road ahead for the next generation of IAMs in general in terms of identifying current challenges and future directions.

7.3 Future Landscape Change Dynamics in Europe: A Multi-Sector, Multi-Model and Multi-Scenario Analysis of Impacts and Adaptation

Europe's human-ecological systems well-being and socio-economic prosperity are intrinsically linked to its natural environment, from clean air and water to fertile soils. Many environmental problems in Europe are caused by complex land use and land cover changes and rapidly expanding urban areas. Various studies illustrated that Europe's land cover has seen significant changes over the past few decades, shaping the overall landscape dynamics. For example, between 1990 and 2000, over 800,000 ha land of Europe has been converted to artificial surfaces (EEA 2006). In addition, Verburg *et al*. (2008) highlighted that future changes in demography, global trade and size of the EU are likely to drive large and rapid land use changes in Europe. Such changes are likely to have important implications on Europe's future landscape quality and value of natural areas (Verburg *et al*. 2008). These changes could also have consequences on potential risks of flooding as well as agricultural production, forestry, biodiversity, and water security issues. This highlights the need for a careful management of land and water resources and appropriate spatial planning of the urban and rural development. This is achieved mainly through a better understanding of the interactions and interdependencies between the various sectors/sub-systems and detecting potential conflicts (negative impacts) and synergies (benefits) in order to develop appropriate planning policy measures. Hence, the analysis of Europe's land use and land cover change dynamics and the risks of associated environmental changes is an important part of planning for sustainable development (EEA 2006).

Scenario-based IA approaches have been widely used in predicting uncertainties of future climate and socio-economic change impacts (e.g., Moss *et al*. 2010). Scenarios describe a set of multiple, equally plausible future developments in an inherently uncertain world. They present plausible evolutions from the current situation, depending on how major driving forces (differentiating between uncertain and predetermined elements) develop and interact, and they help to assess the implications of specific decisions. A scenario-based analysis of impacts can be a useful tool to provide improved understanding of the interrelations between land, water, food and environmental ecosystems and to explore associated cross-sectoral impacts and potential adaptation policy options. However, the development of scenarios poses a methodological challenge, in terms of identifying the key dimensions (which take into account the most relevant factors) along which the various socio-economic systems evolve over time, and it requires systematic approaches that strengthen cross-sectoral perspectives and highlight links between sectors/sub-systems (e.g., Hallegatte *et al*. 2011). This has been demonstrated by the limited number of (i.e., usually four) scenarios commonly used in previous studies considering a two-dimension based scenario development process. As discussed in Section 4.5, such approaches ignore the potential uncertainty of the various driving factors associated with the possible scenario combinations of multi-dimensional drivers of change (e.g., Rozenberg *et al*. 2014). This highlights the need for a comprehensive analysis approach considering several scenario realisations of multiple-driver combinations, which take into account uncertainties of the various individual (climatic or non-climatic) drivers of change. However, at the same time such analysis need to be simple, transparent, and easy-to-understand. This can help decision-makers to anticipate, plan and manage transitions (e.g. demographic changes, climate change, economic development, etc.) successfully and to re-think policies and strategies in a world of complexity and uncertainty.

Integrated approaches help to better understand complex systems by taking into account the key interactions across sectors/sub-systems and scales (e.g., Harrison *et al*. 2013; Holman *et al*. 2005a). The analysis in this study also demonstrated the role of such IAMs and the increasing importance of systems integration approaches for both the scientific and policy community by assessing climate and socio-economic impacts and adaptation on six key land- and water-based sectors/sub-systems in Europe considering a wide range of plausible future scenarios. The study applied the CLIMSAVE IA methodology, based on a multi-sector, multi-model, multi-scale and multi-scenario analysis approach. The analysis took into account the complex interactions between the different sectors/sub-systems under thousands realisations of future climate and socio-economic change scenario settings to identify the key sensitivities and uncertainties of future cross-sectoral impacts and assess the robustness of various adaptation responses across sectors/sub-systems, regions and scenarios. The following sub-sections discuss the key sensitivities and uncertainties of the direct and indirect future impacts in Europe as well as the potential cross-sectoral adaptation and associated key synergies and trade-offs across sectors/sub-systems, regions and scenarios.

7.3.1 Cross-sectoral impacts in Europe: Understanding key sensitivities and uncertainties

As discussed in Section 2.1, the key drivers that affect various sectors/sub-systems in complex and non-additive ways, particularly those indirect drivers with non-linear effects and how impacts interact across sectors/sub-systems and regions, are not generally taken into account in sector-specific studies (e.g., Warren 2011). Such approaches can lead to an under- or over-estimation of projected impacts and hence the cross-sectoral adaptation needed to reduce the severity of future impacts of climate and socio-economic changes across sectors/sub-systems, regions and scenarios. The CLIMSAVE project has demonstrated that systems-thinking and integrated modelling approaches, which take into account the key cross-sectoral and cross-scale interactions, allow a better understanding of the synergies and trade-offs between the various sectors/sub-systems and across regions, which vary depending on the climate and socio-economic drivers and scenario combinations.

There are a number of ways to use the ability of the CLIMSAVE IAP in order to explore cross-sectoral impacts and adaptation under a wide range of 'What-if' scenarios of future changes in climate as well as social, economic, technological, environmental, and policy governance scenario settings. This study assessed the potential cross-sectoral impacts of and uncertainties due to future climate and socio-economic changes in Europe. The assessment used a systematic one-driver-at-a-time (ODAT) sensitivity and multiple-drivers-at-a-time (MDAT) scenario and uncertainty analysis approaches to identify the key sensitivities and uncertainties of future cross-sectoral impacts taking into account the complex interactions between six key land- and water-based sectors/sub-systems: *agriculture*, *biodiversity*, *coasts*, *forestry*, *urban areas*, and *water resources*. The research focussed on seven key indicators, where six of them representing one indicator per sector/sub-system, while the last one representing a combined landscape multi-functionality indicator based on the Shannon diversity index for six different land use classes[23]. These indicators are: (i) *Artificial surfaces*, (ii) *People flooded in a 1 in 100 year coastal and fluvial flood event*, (iii) *Food production*, (iv) *Timber production*, (v) *Land use diversity*, (vi) *Water exploitation index*, and (vii) *Biodiversity vulnerability index*. The assessment

[23] These are: urban, intensive arable, intensive grass, extensive grass, forest and others (e.g., abandoned).

facilitated a comprehensive understanding of the key interdependencies of the food-water-land-ecosystems (FWLE) nexus and the associated potential synergies, conflicts, and trade-offs between the various sectors/sub-systems due to both independent impacts as well as the concurrent interactions of future climatic and socio-economic drivers.

The analysis was based on an extensive application of the CLIMSAVE IAP considering thousands of model runs representing: (1) future changes in individual climatic or non-climatic drivers (as considered in the ODAT analysis, see Chapter 5), and (2) various scenario realisations of the future with combinations of the key (i) climate change drivers only (CD scenarios), (ii) socio-economic change drivers only (SED scenarios), and (iii) combined extreme climate and socio-economic change drivers (C&SED scenarios) (as considered in the MDAT analysis, see Chapter 6). While the various sectoral impact meta-models integrated within the IAP use input data and modelling approach at much finer resolution (e.g., flood model used input data and modelling process at a 100m spatial resolution), the IAP outputs are aggregated at a common 10’ x 10’ spatial grid. The results presented here are then summarised based on: (i) area-average estimates for the five regions (i.e., whole of Europe and the four catchment-based regions: western, southern, eastern, and northern), and (ii) grid-based spatial distribution of future cross-sectoral impacts across Europe.

The regional results showed that the responses of each sectoral indicator and associated interactions across the sectors/sub-systems to ranges of systematic and independent changes in the individual climate and socio-economic drivers and various future scenarios depend on: (i) the direction (positive/negative), magnitude (strong/weak), nature (linear or non-linear) and mechanism (direct or indirect) of the sensitivity (see the ODAT sensitivity analysis results in Chapter 5), and (ii) how the combined effects of the key drivers interact and affect the FWLE nexus under the various climate and socio-economic scenarios (see the MDAT scenario analysis results in Chapter 6). The study also allowed a comprehensive appraisal of and insight into which sectors/sub-systems ‘win’ or ‘lose’ under different scenario futures and identification of the cross-sectoral synergies and trade-offs between various adaptation policies. A synthesis discussion of the results under both the ODAT and MDAT analysis is presented for each sector/sub-system in the sub-sections listed below.

Urban areas: Artificial surfaces

The interactions between urban and rural areas and the highly dynamic, complex and multi-functional nature of urbanisation are important aspects of European landscape change dynamics (Antrop 2004). Over the last decades, a continuous and rapid (at a rate even more than population growth) urban expansion (and/or sprawl) in Europe resulted in a significant urban footprint, threatening the environmental, social and economic balance with significant implications, for example, on water use, enhanced flooding risks, habitat fragmentation and biodiversity loss. For example, between 2000 and 2006, Europe's artificial cover increased by 3.4%, which is by far the largest proportional increase of all land use categories. A better understanding of these interactions and associated changes is vital for managing future urban growth and improved planning of landscapes under changing conditions (Van de Voorde *et al*. 2013). Such information also provides important insights on the extent and magnitude of the potential implications on other sectors/sub-systems, e.g., agriculture, biodiversity, water and flooding. Hence, an integrated view on European urban dynamics in terms of holistic landscape dynamics characterisation, urban growth modelling, and geographic understanding provides an important tool for analysing the potential impacts of future climate, socio-economic and land use changes.

The RUG (Regional Urban Growth) meta-model integrated within the CLIMSAVE IAP represents the start of the meta-model chain and allowed to explore potential future changes in urban growth under a range of future scenario settings. Under the current integrated modelling system, the urban sector/sub-system is sensitive to the socio-economic change drivers/scenarios only. The climatic factors do not influence future urban growth, as the model focusses only on changes in urban development (i.e., in terms of artificial surfaces) that are driven only by socio-economic factors (such as population and GDP) and societal values (such as people's preferences on household location and strictness of planning constraints) (Holman and Harrison 2012). The model also takes into account local geography, travel times with the existing infrastructure and city typology (e.g. mono- versus polycentric).

The analysis results showed that the baseline artificial surfaces at the European scale are estimated at about 3.7%. When looking at the regional artificial cover distributions, the largest concentration of artificial surfaces is estimated in western Europe at6.5%, followed by 4.1%, 3% and 1.2% in eastern, southern and northern Europe, respectively. Future predictions show that urban development increases across Europe (from baseline increasing up to 6.7% in western Europe and 3.2% at the European scale), particularly under those scenarios with significant increases in GDP and, to a lesser extent, population. Although artificial cover accounts for a relatively small percentage of Europe's land area, its dispersed spatial growth pattern (with residential and industrial areas growing at 4 and 7 times the rate of population growth, respectively; EEA 2015) means that more than a quarter of land in Europe is affected by urban land use (EEA 2011). This demonstrates that although European population growth is likely to be relatively small over the coming decades, artificial surfaces may continue to increase as other drivers of increased housing demand and industrial expansion may persist (EEA 2015). The regional differences in urbanisation patterns reflect the differences in spatial planning and the potential for improving future land-use efficiency across Europe.

Coastal and fluvial flooding: People flooded in a 1 in 100 year event

Management of flood risks (both the hazard and potential consequences) is crucial from the perspective of both the socio-economic as well as environmental systems in order to minimize/avoid impacts on people, reduce damages/losses from economic assets, and deal with the implications on natural systems. This is an important aspect of adapting to changing climatic and socio-economic development conditions, which presents significant policy challenges to decision-makers worldwide (de Moel *et al*. 2015). As a result, a-priori and systematic appraisal of the potential impacts and risks of flooding due to future climate and socio-economic changes have become an important part of adaptive flood management planning practices and policies (de Moel *et al*. 2015; Klijn *et al*. 2015). Various studies have demonstrated that the European impacts of flooding (both coastal and fluvial floods) are substantial and growing due to changes in climate and socio-economic factors. Therefore, effective adaptation to and management of the increasing future flood risks require a better understanding of the effects of various climatic and socio-economic drivers of flood risks (Jongman *et al*. 2015). This highlights the need for IA tools at local to regional scales which can allow predicting the potential future impacts (due to both coastal and fluvial flooding) and associated adaptation needs under a range of plausible scenario (climate and socio-economic) futures in order to inform robust adaptation decisions and flood risk management policymaking.

The Coastal Fluvial Flood (CFFlood) meta-model is a broad-scale process-based model, which allows to explore the potential socio-economic (e.g., people flooded) and environmental (e.g., habitat change/loss) impacts of flooding due to a wide range of climatic and socio-economic scenario combinations (Mokrech *et al*. 2015). The model takes into account important interactions with other sectors/sub-systems, including: (i) the urban sector/sub-system, in terms of the effects of changes in residential and non-residential areas (and hence population distribution, including in floodplains) which influences the number of people affected by flooding, (ii) the water sector/sub-system, in terms of the effect of changes in mean river flood flows, which influences the number of people affected by fluvial flooding, (ii) the agriculture sector/sub-system, in which land areas that are lost due to (coastal and/or fluvial) flooding affecting availability of agricultural farm lands; as well as (iv) the biodiversity sector/sub-system, in terms of the environmental impacts of flooding, resulting in changes/losses of wetland habitats, which have a knock-on effect on biodiversity.

This study explored a wide range of scenarios to investigate the key sensitivities and uncertainties of flood impacts in Europe (in terms of the number of people flooded by a 1 in 100 year event), by taking into account the above key cross-sectoral interactions and the independent and combined effects of both climate and socio-economic factors as well as management policies (e.g., the effect of flood protections) considered within the CLIMSAVE integrated framework. The European level baseline estimate of the impacts of flooding (coastal and fluvial combined) without protection indicates that more than 28.3 million people (i.e., approximately 6% of the total population) are currently living within the 100 year flood event (see Chapter 5). These estimates are generally consistent with previous studies (e.g., Jongman *et al*. 2012). About 66% of these people are concentrated in western Europe, while about 17% and 13% are located in eastern and southern Europe, respectively. However, when flood defences are considered, the number of people flooded at the European scale is reduced to about 17.4 million (under minimum protection) and 0.74 million (under maximum protection). This highlights the benefits of defences (and adaptation more generally) in reducing impacts. Moreover, the results showed that flood impacts across Europe will generally increase in the future, especially due to sea-level rise and growing population (see Chapter 6). When the various plausible climate and socio-economic scenarios are considered, the overall uncertainty range of these impacts at the European scale is estimated between -11 and +27% change from baseline. Regionally, these ranges increase up to between -18% and +88% in eastern Europe. The results also showed that these impacts, including those due to more extreme scenarios (e.g., a >1m sea-level and/or 50% population increase), can only be reduced to current levels by significant adaptation measures such as upgrading flood protection standards by 500% or more from baseline levels (Mokrech *et al*. 2015).

Land use and land cover change: Food production, timber production, and land use diversity

Agriculture is the main and most important land cover type in Europe in terms of the proportion of the total land area occupied and its significant economic importance (van Delden *et al*. 2010). It covers more than 45% of the land surface, compared to other sectors/sub-systems such as forest and semi-natural land and urban areas (e.g., EEA 2006). Furthermore, food production remains as one of the most pressing public policy issues, in view of long-term global population pressures and the need to adapt to global environmental change. Europe's agriculture policy plays an important role both in terms of planning sustainable development and landscape preservation as well as its role as a global trade partner (van Delden *et al*. 2010). At the regional level, there are growing concerns about food security across Europe, as it depends on many other resources such as availability and productivity of land and supplies of water and managing the trade-offs in land uses and sectors/sub-systems (e.g., between agriculture, forests, and urban and water), alongside new pressures for local and urban food supply systems. In addition, increasing food prices are often considered as a key sign of growing natural resources constraint (Ringler *et al*. 2013).

Moreover, forests play an important role both from socio-economic and environmental perspectives, ranging from timber and fuel production to non-timber forest products (such as conservation of soil, water and biodiversity, providing wildlife habitats, tourism and recreational opportunities, etc.) to functioning as carbon storage and for landscape diversity (Kirilenko and Sedjo 2007). Forests in Europe are the second largest land cover following agricultural land, where forests and semi-natural land accounts for about 37% (~176 million ha) of Europe's total land area (Hanewinkel *et al*. 2013). However, it is likely that future climatic and socio-economic changing conditions will have significant direct and indirect implications on both natural and modified forests in the future (Kirilenko and Sedjo 2007), which could lead to either positive or negative impacts across Europe (e.g., Solberg *et al*. 2003). In addition, land use change, for example associated with expansion of agriculture, also presents important challenges, where future policy decisions in various sectors/sub-systems (e.g., agriculture, forestry and conservation sectors/sub-systems) are leading to intensifying competition for land (Smith *et al*. 2010). This could have negative effects such as loss of forest areas, for example, causing a decline in timber production in the future.

Such phenomena demonstrate the interdependence and feedback effects between various sectors/sub-systems and associated factors that exist and propagate through the entire food-water-land-ecosystems (FWLE) nexus across scales. For example, given that agriculture (mostly irrigated) accounts for about one-third of the total water withdrawals in Europe the food security and water scarcity issues may arise out of reductions in agricultural land area and/or decreases in available water supplies that result from various interacting factors such as urbanization and industrialization, soil erosion, desertification, and land degradation, as well as, poor management of water and other environmental resources. In addition, future climate and socio-economic changes present increased risks to the FWLE nexus as more frequent extreme events such as floods, droughts and heat waves cause large negative impacts on the food, water, forest, and ecological systems, which raises key challenges in terms of food security, loss of biodiversity, and a decline in suitable land and water resources. Furthermore, the high degree of uncertainty in future climate conditions makes planned adaptation difficult. Hence, understanding the cross-sectoral interactions and associated impacts of future climatic and socio-economic conditions is central to robust adaptation planning (Harrison *et al*. 2016) and how we manage the various resources in a sustainable and efficient way. This demonstrates the potential benefits of the nexus-thinking and integrated resources management approaches and cross-sectoral adaptation responses in order to optimise the FWLE nexus by improving resources use efficiency for a better advancement of human well-being and environmental sustainability (Ringler *et al*. 2013). Moreover, such approaches help avoid adverse impacts of single-sector based development strategies that could otherwise compromise long-term management of resources and sustainable development planning.

Different studies have used various approaches to assess climate change impacts on agriculture rural development, with different metrics giving different predictions of future risks. In addition, most studies including integrated assessments often focus on direct impacts and integration of components of the sector/sub-system (e.g., van Ittersum *et al*. 2008), and indirect impacts (through, for example, sea-level rise, storms, pests and diseases) have not be been quantified (Gornall *et al*. 2010). Furthermore, interactions with other sectors/sub-systems are often given limited attention, and hence in informing integrated policymaking. As a result, the bound of uncertainty in estimates of the impacts of climate change on agriculture (e.g., crop yield) are generally increasing as highlighted in Rotter (2014). The CLIMSAVE approach demonstrates the potential benefits of combining simplified models of farm profitability (SFARMOD) and water availability (WGMM) with models of crop (CropYields meta-model) and forest (metaGOTILWA+) yields to predict future rural land use changes and associated cross-sectoral impacts in Europe (Audsley *et al*. 2015). The various models integrated within the CLIMSAVE IAP allow exploring the potential direct and indirect impacts of various future climatic and socio-economic scenarios by taking into account important interactions of impacts across the sectors/sub-systems, regions and scenarios.

The results showed that under the current integrated modelling system; agriculture and food production remains an important driver of Europe's future land use and landscape change dynamics. The results also highlighted that in contrast, the socio-economic factors (such as population growth, food imports, and improvement in agricultural yield due to technology and agronomy) have greater impacts on food production, than climate. The model analysis shows that the European total food production at the baseline is estimated around 9.8 million TJ, where 48% of the total is concentrated in western Europe, followed by a 25% and 21%

production estimate in southern and eastern Europe, respectively. However, when the various plausible future climate and socio-economic scenarios are considered, the uncertainty range in future European scale food production is estimated between a -26% decline and a +29% increase from baseline across the scenarios. These changes in agricultural production have significant indirect implications on forestry, biodiversity, and water.

Based on this analysis, the current timber production at the European scale is also estimated at just over 262Gt, with a 41%, 28%, 18%, and 14% distribution across the western, northern, eastern and southern European regions, respectively. Similarly, when the various 'not-implausible' climate and socio-economic scenarios are considered, the European scale future timber production shows an uncertainty ranging between a -35% decline and a +25% increase from baseline across all the scenarios. These changes are mainly driven by changes in agricultural land use, demonstrating the potential implications and policy challenges that the issues of food security could bring, and what it means if Europe is to produce all its food internally, without relying on imports from outside. Moreover, when looking at the land use diversity index, the results demonstrate that while agricultural land use expansion into new areas (including at the expense of forest areas) is identified as the main driver, the indicator shows more complex response to changes in both climate and socio-economic scenarios. As the indicator represents six different land use classes, the varying responses under the future scenarios are associated with the complex interactions between the various land use classes. The key pattern is that scenarios that encourage increased food production into new areas leads to a decline in diversity, as the expansion of agricultural land use replaces other land use classes.

Water resources and use: Water exploitation index

Water related issues such as water scarcity, flooding, and droughts have already affected and still present important socio-economic and environmental implications and policy challenges across large parts of Europe (EEA 2010a). Various studies have also demonstrated that future climate change (e.g., in terms of changes in temperature and precipitation) and growing socio-economic pressures (such as due to population and GDP changes) are expected to affect Europe's future water availability (e.g., change in annual river flows) and uses (e.g., increased irrigation water withdrawals in Mediterranean regions) (e.g., Table 2.1). Projected impacts include strong changes in annual river flows (e.g., with a significant decline in many parts of southern and south-eastern regions, while increasing in northern and north-eastern Europe) and seasonal runoffs (e.g., with higher winter flows with potential risk of flooding in northern and north-eastern areas, while with lower summer flows in drought prone and water stressed areas in southern and south-eastern regions) (Flörke *et al*. 2011). The changes and potential future impacts highlight the need for the human and natural environment systems to be prepared for such extremes and their concurrent occurrences. In addition, future use and management of Europe's water resources and planning policies need to take into account these changes and associated risks of flooding, droughts and water stress. This is important in order to adapt to, and/or cope with, future impacts across various sectors/sub-systems, including agriculture (e.g., irrigation water use), flooding (e.g., risks of fluvial and coastal flooding), ecosystems (e.g., change in minimum environmental flow requirements), etc.

Furthermore, a comprehensive assessment of the potential cross-sectoral and cross-regional impacts induced by various possible future scenarios of key climatic and socio-economic factors is important. This is because such assessment will be vital for identifying which sectors/sub-systems and regions will be particularly more affected and helps for planning appropriate response strategies to reduce negative effects on human wellbeing and aquatic ecosystems (Wimmer *et al*. 2015). In this context, a number of methods have been developed and various studies have assessed future impacts considering different scenarios and approaches (Section 2.1.6). The CLIMSAVE approach used a system of coupled sectoral water resources management meta-models of water availability (that simulate the characteristic macro-scale behaviour of the terrestrial water cycle) and water use (human use in the domestic, manufacturing industry, electricity generation, and agricultural sectors/sub-systems as well as considering the minimum environmental flow requirements) (Wimmer *et al*. 2015). The coupled model systems allow assessing the impacts of a range of future climate and socio-economic scenarios and exploring the potential effects of different generic water allocation schemes in Europe. The integrated approaches/frameworks within the CLIMSAVE IAP provide a better understanding of the key interactions across the sectors/sub-systems and regions in terms of the competition for water and associated cross-sectoral impacts, so appropriate adaptation measure can be devised.

The analysis in this study focussed on the water exploitation index (WEI) as a key indicator, which combines data on both water availability and withdrawals (which is also referred as withdrawals-to-availability index). This provided the integrated effects of various climatic and socio-economic factors from the perspective of both the pressure from human society (the demand side) and changes in the hydrological system (the supply side) to identify which sectors/sub-systems and regions are most affected by water stress. A region is characterized as being under low water stress, if WEI exceeds 20%, and under high stress if WEI exceeds 40%.

The results showed that significant water resource shortages may result from future climate and socio-economic changes in many European regions, particularly in the southern region (Chapters 5 and 6; Wimmer *et al*. 2015). At the baseline, while the European scale WEI is estimated at about 0.15 (indicating low water stress), in southern Europe water stress is estimated with greater than 27% (a moderate stress). However, when the various plausible future climate and socio-economic scenarios are considered the uncertainty range in water stress at the European level is estimated between a relatively moderate -46% decline and a significant +140% increase in WEI from baseline. These results highlight that most European water resources will experience significant pressure and are likely to be insufficient to meet the various sectoral water demands for human use and the minimum flow requirements for aquatic ecosystems in many regions. This requires designing appropriate water allocation adaptation schemes in order to reduce future impacts across the sectors/sub-systems and regions (Wimmer *et al*. 2015).

Biodiversity: Biodiversity vulnerability index

Changing/loss of biodiversity leads to a change in ecosystem processes and alters ecosystems' resilience to environmental change, which has significant consequences for the vital services that ecosystems provide for supporting human wellbeing and health of the natural systems (Chapin *et al*. 2000). The recent report on 'The European Environment: State and Outlook 2015' highlighted that almost 60% of protected areas and 77% of habitat types in Europe are considered in unfavourable conservation status resulting in loss of biodiversity (EEA 2015). One of Europe's main targets of halting loss of biodiversity is to maintain and enhance its ecosystems and their services by establishing green infrastructure and restoring at least 15% of those degraded ecosystems by 2020. Examples of planned strategies to achieving this target include increasing contribution of agriculture and forestry in reducing ecosystems degradation and ensuring conservation of species and habitats through environmental-friendly and sustainable use of resources across these sectors/sub-systems. However, meeting the overall target still remains a challenge (EEA 2015). Future climate change will have important implications on Europe's biodiversity, as impacts are projected to intensify and the underlying drivers of change/loss are expected to persist. In addition to climate change, indirect impacts due to rapid land use changes associated with various socio-economic factors also play an important role in the sustainability of Europe's biodiversity in the years/decades ahead. As a result, various studies highlighted the need to identify those species and regions that are likely to be most vulnerable to the direct and indirect impacts of both climate and socio-economic changes in order to reduce future changes and loss of biodiversity (e.g., Galli *et al*. 2014; Larigauderie *et al*. 2012).

A number of approaches have been developed and applied to assess biodiversity vulnerability to climate change, as discussed by Pacifici *et al*. (2015). The SPECIES meta-model integrated within the CLIMSAVE IAP allows to simulate and explore the potential direct and indirect impacts of both climatic and socio-economic factors and associated land use changes on the potential geographical distribution of 12 selected species associated with different habitats that interact with the various sectors/sub-systems, including agricultural, coastal and water environments. This study considered a wide range of scenarios to investigate the key sensitivities and uncertainties of future biodiversity vulnerability in Europe in order to identify which regions are more vulnerable and by how much. The results showed that at the European scale, while there are some (13%) improvement in vulnerability in some areas particularly in the north, over 37% of species could lose appropriate climate and/or habitat space under the various plausible climate and socio-economic scenarios. Regionally, while the highest improvement (a reduction in vulnerability by up to 32%) is estimated in northern Europe, up to 54% increase in biodiversity vulnerability is projected in southern Europe, reflecting a potential south-to-north shift of some species, especially under warmer scenarios. This highlights the need for Europe wide implementation of appropriate measures to reduce future biodiversity losses across Europe.

7.3.2 Cross-sectoral implications of adaptation: Key synergies, conflicts and trade-offs

Long-term sustainable and climate-resilient development planning requires acknowledging and understanding that many of the key natural resources (e.g., land, water, food etc.) are finite (Weitz *et al*. 2014). These resources are needed to support vital ecosystem services, but critical trade-offs and conflicts can be observed as the various sectors/sub-systems interact, for example, when food and timber production compete for land and when the expansion of one impedes the other, as discussed in Section 7.3.1. Therefore, understanding the key sensitivities of impacts and uncertainties across these sectors/sub-systems and scales (both in space and time) is important for efficient resource management and devising robust adaptation as well as mitigation policy responses under uncertain climate and socio-economic changes.

Climate change adaptation is one of the biggest challenges that humanity faces through the 21st century (Jones *et al*. 2012). While there is a significant focus on adaptation strategies based on hard-engineering structures (e.g., sea walls, irrigation infrastructure and dams, etc.), future adaptation planning need to consider broader spectrum of adaptation strategies (Jones *et al*. 2012). This requires combined approaches integrating various adaptation strategies (Cheong *et al*. 2013), such as environmental (Jones *et al*. 2012; Cheong *et al*. 2013; Temmerman *et al*. 2013), technological (Biagini *et al*. 2014; Olhoff 2015; e.g., water saving technologies; Zou *et al*. 2013), and behavioural (Spence *et al*. 2011; Clayton *et al*. 2015; e.g., reducing consumption and waste; Stoll-Kleemann and O'Riordan 2015) adaptation approaches. Such adaptation approaches can also provide flexible alternatives for adapting to the potential impacts of future climate change.

Adaptation strategies in terms of the management of human and natural systems (ranging from food production to forestry to biodiversity protection to risk management) have regional nature and hence need regional understanding of potential future impacts and associated adaptation needs (Hibbard and Janetos 2013). The decision-making process in adaptation also has regional nature, as it is often manifested by the responses to global socio-economic change indicators. Hibbard and Janetos (2013) also highlighted that "One of the major complications in understanding and responding to global changes is that they are often characterised by multiple interactions, feedbacks, and trade-offs among different human activities and environmental processes across both temporal and spatial scales. For example, energy supply, urban development, and agricultural production often compete for land and water resources. The extent and productivity of agricultural land depends on availability of water supply, weather, and market demand, among many other factors" (p.568). This highlights the need for a holistic understanding of such interactions for devising appropriate adaptation strategies.

Achieving effective adaptation requires an integrated and holistic approach to managing the wide ranges of the potential impacts due to the concurrent effects of both climate and socio-economic factors, and cross-sectoral integration of adaptation policies (e.g., Burley *et al*. 2015). However, adaptation decisions are often made without sufficient attention to cross-sectoral and cross-regional interrelationships of impacts, targeting sector/sub-system- and region-specific goals and, in so doing, resulting in trade-offs and associated potential risks and uncertainties across various sectors/sub-systems and regions. In order to ensure the optimal management of trade-offs and the maximization of overall synergies/benefits, adaptation decision-making processes need to be reflective of this and take into account the dynamic nature of complex systems involved across sectors/sub-systems and regions. As a result, increasing attention is now being given to the potential risks and opportunities that the cross-sectoral interdependencies between sectors/sub-systems and adaptation strategies bring under a changing climate (e.g., Hall *et al*. 2012). Integrated analysis and modelling approaches play a crucial role in assisting climate change adaptation and mitigation policymaking by capturing the key interactions between society and the environment and providing a better understanding of the nexus in order to design, appraise, and prioritise appropriate response options that are feasible across different sectors/sub-systems and scales. A wide range of integrated concepts, frameworks and assessment methods have been developed and applied to understand such interdependencies between various sectors/sub-systems to varying level of details and integration (Sections 2.3 and 2.4). However, no prior studies have looked at the quantitative inter-linkages between food, water, land, and ecosystems in Europe to a sufficient level of detail as well as simplicity to be relevant for policy and decision-makers to inform robust adaptation planning. Hence, the challenge in developing appropriate conceptual approaches and IA tools that can provide scientifically reliable and policy-relevant information for devising an integrated, long-term and multi-sectoral climate change adaptation and mitigation policies still remains.

The study also explored the robustness of different adaptation policies based on an extensive application of the CLIMSAVE IAP considering a wide range of climate and socio-economic change scenarios. The analysis particularly focussed on scenarios that cover uncertainty of the extreme European scale cross-sectoral impacts on each of the seven selected sectoral indicators. The study considered four classes of adaptation policies (as detailed in Section 4.6): (i) *Behavioural adaptation* (BA), (ii) *Environmental adaptation* (EA), (iii) *Technological adaptation* (TA), and (iv) *Combined adaptation* (CA). The results demonstrate that there are important cross-sectoral trade-offs and synergies (in terms of the effects of adaptation in reducing impacts relative to ‘without adaptation’) between the adaptation polices across the sectors/sub-systems, regions, and scenarios. Figure 7.1 presents a summary of the effects of adaptation in terms of the % change in indicators at the baseline (BL), and under 13 climate scenarios (CD), 16 socio-economic scenarios (SED), and 4 combined extreme climate and socio-economic change scenarios (C&SED).

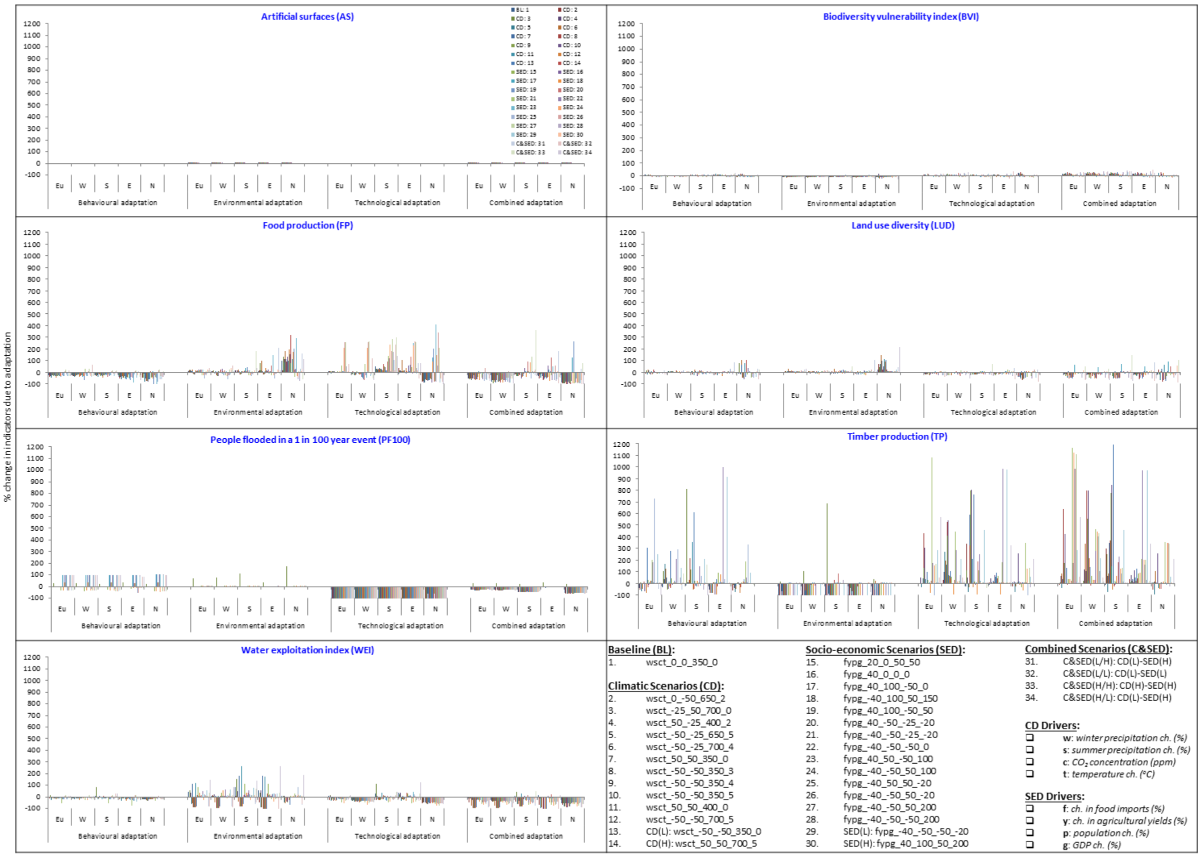


Figure 7.1: *The effect of adaptation as % change in indicators under the various CD, SED, and C&SED scenarios.*

The results demonstrate that the highest benefit of the adaptation policies is estimated for TP with about a 12-fold improvement under the CA policy, particularly under the CD scenarios. In contrast, for urban (i.e., artificial surfaces) the effects are estimated very small/insignificant (Figure 7.1). Comparing results across the sectors/sub-systems and regions, all except the CA policy shows robustness with respect to the geographical scale, in terms of improving all sectoral indicators across all the five regions under at least one scenario. For example, under three of the SED scenarios (i.e., SED-24, 26, 27; Figure 7.1), all sectors/sub-systems improve across all regions due to the TA policy. Similarly, all sectors/sub-systems show improvement across all the five regions due to the BA policy under one of the SED scenarios (i.e., SED-18), while improving due to the EA policy under one of the C&SED scenarios (i.e., C&SED-32). However, although there is robustness for at least one sector/sub-system with respect to the geographical scale (i.e., an improvement of an indicator due to adaptation across all the five regions; Figure 7.1), the results show that there is no robustness across the sectors/sub-systems due to any of the policies under all the CD scenarios. The sectoral robustness of the adaptation policies based on ranking of the % change in the indicators after adaptation across the regions and scenarios is discussed as follows.

Urban areas: Artificial surfaces

Table 7.1 presents a summary of the effects of each adaptation policy for AS across the various scenarios. The results demonstrate that although there is robustness across the regions under some of the scenarios, the overall effect (in terms of the magnitudes of change) of each adaptation policy on AS is insignificant. The extreme % changes (i.e., max. ↓ and ↑) in AS under all the adaptation policies ranges only between a 0.3% decline in western Europe under the SED scenarios (i.e., SED-24) and a very small (just 0.003%) increase in AS in eastern Europe at the baseline and under all the CD scenarios, both due to the EA and CA policies.

Table 7.1: *The % change in AS with and without adaptation under the various CD, SED, and C&SED scenarios.*

Artificial sutrfaces (AS)		Behavioural					Environmental					Technological					Combined				
		Eu	W	S	E	N	Eu	W	S	E	N	Eu	W	S	E	N	Eu	W	S	E	N
BL	1	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
CD	2	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
	3	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
	4	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
	5	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
	6	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
	7	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
	8	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
	9	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
	10	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
	11	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
	12	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
	13	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
	14	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
SED	15	0.0	0.0	0.0	0.0	0.0	-0.1	-0.2	-0.1	-0.1	0.0	0.0	0.0	0.0	0.0	0.0	-0.1	-0.2	-0.1	-0.1	0.0
	16	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
	17	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
	18	0.0	0.0	0.0	0.0	0.0	-0.1	-0.3	-0.1	-0.1	0.0	0.0	0.0	0.0	0.0	0.0	-0.1	-0.3	-0.1	-0.1	0.0
	19	0.0	0.0	0.0	0.0	0.0	-0.1	-0.2	-0.1	0.0	0.0	0.0	0.0	0.0	0.0	0.0	-0.1	-0.2	-0.1	0.0	0.0
	20	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
	21	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
	22	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
	23	0.0	0.0	0.0	0.0	0.0	-0.1	-0.3	-0.1	-0.1	0.0	0.0	0.0	0.0	0.0	0.0	-0.1	-0.3	-0.1	-0.1	0.0
	24	0.0	0.0	0.0	0.0	0.0	-0.1	-0.3	-0.1	-0.1	-0.1	0.0	0.0	0.0	0.0	0.0	-0.1	-0.3	-0.1	-0.1	-0.1
	25	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	-0.1	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	-0.1	0.0
	26	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	-0.1	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	-0.1	0.0
	27	0.0	0.0	0.0	0.0	0.0	-0.1	-0.2	-0.1	-0.1	0.0	0.0	0.0	0.0	0.0	0.0	-0.1	-0.2	-0.1	-0.1	0.0
	28	0.0	0.0	0.0	0.0	0.0	-0.1	-0.2	-0.1	-0.1	0.0	0.0	0.0	0.0	0.0	0.0	-0.1	-0.2	-0.1	-0.1	0.0
	29	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
	30	0.0	0.0	0.0	0.0	0.0	-0.1	-0.2	-0.1	-0.1	0.0	0.0	0.0	0.0	0.0	0.0	-0.1	-0.2	-0.1	-0.1	0.0
C&SE	31	0.0	0.0	0.0	0.0	0.0	-0.1	-0.2	-0.1	-0.1	0.0	0.0	0.0	0.0	0.0	0.0	-0.1	-0.2	-0.1	-0.1	0.0
	32	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
	33	0.0	0.0	0.0	0.0	0.0	-0.1	-0.2	-0.1	-0.1	0.0	0.0	0.0	0.0	0.0	0.0	-0.1	-0.2	-0.1	-0.1	0.0
	34	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0

KEY:

Ranking colour code:			
%ch	Rank	↑	↓
0 - 10%	No ch.		
10 - 50%	Low		
50 - 100%	Medium		
> 100%	High		

Coastal and fluvial flooding: People flooded in a 1 in 100 year event

Table 7.2 presents a summary of the effects of each adaptation policy and ranking of the % change in PF100 'after adaptation' relative to 'no adaptation' both at the baseline and under the various climate and socio-economic change scenarios. Comparing the results across the five European regions, it can be seen that all except the EA policies show robustness across the geographical scale at least under one scenario. Particularly, the TA policy shows robustness across all regions and scenarios with a 'high' reduction in PF100 (i.e., by over 56%) across all the five regions and at the baseline as well as the various CD and SED scenarios. Similarly, except for one of the CD scenarios (i.e., CD-3, where PF100 increases by 21–33% across the regions) the CA policy also shows robustness across all the regions and the scenarios. Hence, the results suggest that both the TA and CA policies are more robust with respect to the geographical scale as well as to the uncertainty of future CD and SED scenarios.

In contrast, when looking at the effects of the EA policy, the results show that the residual impacts are almost the same as those impacts without adaptation (Table 7.2) with very small/no change in PF100 after adaptation. The exception is under one of the CD (i.e., CD-3) scenario, where FP100 with adaptation increases by 38-172% more than with no adaptation across all the regions. This shows the conflicting effects (trade-offs) of the environment focussed adaptation policy (EA) on PF100, as the policy focusses mainly on creating/maintaining wetland habitats in rural coastal and fluvial floodplains where there less/no people and economic assets, but highlighting the potential for increasing (in relative terms) flood impacts on people under some scenarios.

However, when looking at the effect of the BA policy, although PF100 (with adaptation) is unchanged with respect to that of with no adaptation under almost all of the CD scenarios, it increases by up to 28% at the European scale and between 21% (southern and northern Europe) and 33% (eastern Europe) under the CD scenario (with CO_2=700ppm, WPrec=-25%, and SPrec=+50%; Table 7.2). Similarly, PF100 increases by at least 30% under the various SED and by more than 83% under the C&SED scenarios. The results suggest that there is robustness with respect to the geographical scale for seven of the 16 SED scenarios (with a 14-56% decline in PF100 across the regions due to adaptation) and two of the 4 C&SED scenarios (with a 14-43% decline in PF100 across the regions due to adaptation) (Table 7.2). The BA policy is less robust to the uncertainty regarding future scenarios, particularly changes in the socio-economic drivers.

Table 7.2: *The % change in PF100 with and without adaptation under the various CD, SED, and C&SED scenarios.*

		People flooded in a 1 in 100 year event (PF100)																			
		Behavioural					Environmental					Technological					Combined				
		Eu	W	S	E	N	Eu	W	S	E	N	Eu	W	S	E	N	Eu	W	S	E	N
BL	1	0	0	0	0	0	0	0	0	0	0	-100	-100	-100	-100	-100	-27	-29	-47	-4	-56
CD	2	0	0	0	0	0	0	0	0	0	0	-100	-100	-100	-100	-100	-30	-33	-46	-4	-59
	3	28	26	21	33	21	73	77	113	38	172	-100	-100	-100	-100	-100	28	26	21	33	21
	4	0	0	0	0	0	0	0	0	0	0	-100	-100	-100	-100	-100	-26	-28	-44	-4	-56
	5	0	0	0	0	0	0	0	0	0	0	-100	-100	-100	-100	-60	-30	-32	-47	-5	-60
	6	0	0	0	0	0	0	0	0	0	0	-100	-100	-100	-100	-100	-30	-33	-46	-4	-60
	7	0	0	0	0	0	0	0	0	0	0	-100	-100	-100	-100	-100	-33	-36	-49	-12	-57
	8	0	0	0	0	0	0	0	0	0	0	-100	-100	-100	-100	-100	-31	-35	-46	-5	-60
	9	0	0	0	0	0	0	0	0	0	0	-100	-100	-100	-100	-100	-30	-33	-47	-5	-60
	10	0	0	0	0	0	0	0	0	0	0	-100	-100	-100	-100	-100	-31	-33	-46	-5	-60
	11	0	0	0	0	0	0	0	0	0	0	-100	-100	-100	-100	-100	-26	-29	-42	-3	-55
	12	0	0	0	0	0	0	0	0	0	0	-100	-100	-100	-100	-100	-31	-33	-46	-5	-60
	13	0	0	0	0	0	0	0	0	0	0	-100	-100	-100	-100	-100	-31	-35	-47	-4	-60
	14	0	0	0	0	0	0	0	0	0	0	-100	-100	-100	-100	-100	-25	-28	-43	-4	-55
SED	15	-32	-37	-28	-21	-43	0	1	1	-2	1	-100	-100	-100	-100	-59	-28	-28	-46	-6	-59
	16	0	0	0	0	0	0	0	0	0	0	-100	-100	-100	-100	-100	-27	-29	-47	-4	-56
	17	100	100	100	100	102	0	0	0	0	0	-100	-100	-100	-100	-100	-27	-29	-47	-4	-56
	18	-32	-36	-36	-14	-44	0	0	0	-1	1	-100	-100	-100	-100	-100	-30	-29	-46	-5	-56
	19	100	100	100	100	102	0	0	0	0	0	-100	-100	-100	-100	-100	-27	-29	-47	-4	-56
	20	32	33	33	30	33	0	0	0	0	0	-100	-100	-100	-100	-100	-27	-29	-47	-4	-56
	21	32	33	33	30	33	0	0	0	0	0	-100	-100	-100	-100	-100	-27	-29	-47	-4	-56
	22	100	100	100	100	102	0	0	0	0	0	-100	-100	-100	-100	-100	-27	-29	-47	-4	-56
	23	100	100	100	100	102	0	0	0	0	0	-100	-100	-100	-100	-100	-27	-29	-47	-4	-56
	24	-32	-36	-34	-15	-45	0	0	1	-1	1	-100	-100	-100	-100	-100	-29	-29	-46	-6	-57
	25	-34	-22	-19	-56	0	0	-2	-1	2	0	-100	-100	-100	-100	-100	-21	-26	-48	-3	-56
	26	-34	-22	-19	-56	0	0	-2	-1	2	0	-100	-100	-100	-100	-100	-21	-26	-48	-3	-56
	27	-32	-36	-37	-14	-43	0	0	0	-1	1	-100	-100	-100	-100	-100	-30	-29	-46	-5	-56
	28	100	100	100	100	102	0	0	0	0	0	-100	-100	-100	-100	-100	-27	-29	-47	-4	-56
	29	96	100	100	85	101	0	0	0	0	0	-100	-100	-100	-100	-100	-27	-29	-47	-4	-56
	30	-32	-36	-37	-14	-43	0	0	0	-1	1	-100	-100	-100	-100	-100	-30	-29	-46	-5	-56
C&SE	31	-33	-36	-38	-14	-43	0	0	0	-1	1	-100	-100	-100	-100	-100	-34	-35	-46	-6	-60
	32	95	100	100	83	101	0	0	0	0	0	-100	-100	-100	-100	-100	-30	-35	-47	-4	-61
	33	-32	-36	-37	-14	-43	0	0	0	-1	1	-100	-100	-100	-100	-56	-28	-28	-42	-5	-55
	34	96	100	100	86	101	0	0	0	0	0	-100	-100	-100	-100	-100	-25	-28	-43	-3	-55

KEY:			
Ranking colour code:			
%ch	Rank	↑	↓
0 - 10%	No ch.		
10 - 50%	Low		
50 - 100%	Medium		
> 100%	High		

Land use and land cover change: Food production, timber production, and land use diversity

Tables 7.3–7.5 present a summary of the effects of each adaptation policy in terms of ranking of the % change in FP, TP, and LUD before and after adaptation under the various climate and socio-economic change scenarios. For FP, all except the CA adaptation policies have at least one scenario under which FP increases (although with different magnitude) across the five regions. This suggests that there is robustness across the geographic scale. When considering the baseline and the CD scenarios, only the EA adaptation policy leads to an increase in FP across all the five regions at least under one scenario, with the highest increase (by a factor of 3.2 under the CD-14 scenario) estimated in northern Europe, while other regions with low (up to 10%) to medium (up to 50%) increase in FP with respect to no adaptation.

In contrast, comparing the results across the SED scenarios suggest that CA is the only policy that does not increase FP across the regions under any of the scenarios. However, BA, EA and TA policies show robustness with respect to the uncertainty across the SED scenarios by increasing FP across the regions under up to three of the scenarios (Tables 7.3). In terms of the magnitudes of change, TA is more robust with respect to the geographic scale, with a high (more than 100%) increase in FP across all regions under three SED scenarios. The effects of adaptation in increasing FP are estimated as 'low' (ranging between 13-22%) under the BA policy and between 'no/insignificant' change and 'medium' increase under the EA policy across the regions (except the high increase in eastern and northern Europe under the SED-23 scenario). However, when the C&SED scenarios are considered, only the EA policy shows robustness under two of the four C&SED scenarios with an increase in FP by up to 8-110% across the scenarios.

When evaluating robustness across the scenarios, the results illustrate that except for TA (in southern Europe) and EA (in northern Europe); all adaptation policies do not increase FP across all the CD scenarios in any of the European regions. Similarly, except for TA (in southern Europe), this is also true across all the SED scenarios. In terms of the C&SED scenarios, the exceptions are for EA both at the European scale and in western Europe as well as for TA in southern Europe (Tables 7.3). These results suggest that while there is robustness in the EA and TA policies for some regions as highlighted above, the BA and CA adaptation policies are generally less robust in terms of the uncertainty in future climate and socio-economic scenarios. When looking at the European scale alone, all adaptation policies also show no robustness with regard to the uncertainty in all the scenarios.

Table 7.3: *The % change in FP with and without adaptation under the various CD, SED, and C&SED scenarios.*

		Food production (FP)																			
		Behavioural adaptation					Environmental					Technological					Combined adaptation				
		Eu	W	S	E	N	Eu	W	S	E	N	Eu	W	S	E	N	Eu	W	S	E	N
BL	1	-28	-25	-24	-40	-34	11	2	15	11	100	3	-13	49	-10	-31	-53	-80	-11	-35	-87
CD	2	-38	-34	-30	-52	-44	12	6	17	17	16	4	5	11	32	-81	-56	-70	-19	-51	-94
	3	-28	-28	-25	-33	-45	20	13	-2	79	132	2	-18	28	16	-72	-61	-93	-35	-20	-96
	4	-31	-31	-29	-40	-13	12	-2	12	7	109	-1	-7	31	13	-88	-54	-71	-7	-49	-97
	5	-46	-41	-44	-60	-79	1	-13	9	15	85	-12	-29	24	9	-91	-66	-82	-37	-48	-99
	6	-27	-30	-15	-32	-55	19	-5	23	96	183	4	-24	28	105	-49	-60	-79	-32	-12	-95
	7	-29	-26	-18	-47	-54	11	9	2	10	115	1	-20	38	-4	-61	-54	-86	-21	-37	-85
	8	-30	-20	-23	-47	-75	-16	-28	-20	-18	91	0	-5	19	8	-67	-57	-65	-27	-65	-100
	9	-33	-24	-31	-45	-78	-18	-32	-21	-18	100	9	6	27	18	-69	-24	-25	-5	-24	-86
	10	-28	-21	-24	-35	-81	-16	-33	-16	-15	131	2	-8	29	14	-73	-60	-59	-51	-61	-99
	11	-34	-22	-36	-52	-59	10	7	7	6	95	-3	-12	22	-8	-67	-55	-84	-19	-46	-82
	12	-47	-41	-48	-62	-64	18	5	5	34	193	-3	-21	16	38	-36	-66	-83	-40	-43	-98
	13	-31	-19	-24	-59	-62	11	-1	-7	16	155	0	-6	44	-15	-69	-61	-72	-34	-53	-96
	14	-27	-30	-1	-39	9	17	23	8	7	320	4	-20	67	1	-58	-60	-88	-12	-49	-100
SED	15	-33	-29	-26	-48	-50	3	-5	14	-5	81	2	-15	51	-6	-61	-42	-69	18	-42	-87
	16	-23	-26	-17	-22	-41	19	29	7	20	-3	0	-42	44	55	-87	-12	-64	36	58	-77
	17	-35	-41	-28	-53	0	15	-11	33	-12	112	-1	-45	13	8	123	7	-16	8	22	125
	18	-30	-32	-17	-36	-56	13	5	5	2	174	2	-9	4	1	93	-71	-86	-39	-74	-95
	19	-39	-71	-19	-68	-100	20	-30	44	5	201	-1	-59	15	60	205	-16	-71	5	9	266
	20	-34	-31	-40	-40	-25	19	13	13	59	25	-1	-66	88	130	-85	-4	-71	91	126	-63
	21	-1	30	-20	-4	-42	-27	-27	-25	-24	-38	59	71	139	41	-74	-50	-77	1	-30	-96
	22	-29	-18	-32	-44	-45	-7	-14	-4	-8	28	5	-27	116	-13	-85	-63	-85	-8	-67	-92
	23	-33	-36	-28	-89	-100	21	9	15	150	289	2	-50	2	252	413	-22	-69	-11	53	-55
	24	-14	-19	-12	-7	-13	-29	-32	-28	-23	-35	211	207	237	231	143	-13	-47	87	-14	-92
	25	-34	-31	-29	-18	-85	-52	-60	-35	-53	-58	11	1	9	9	54	-74	-81	-53	-70	-98
	26	7	3	9	7	15	-20	-24	-9	-11	-48	259	255	181	261	343	33	5	110	54	-89
	27	21	28	17	13	22	9	20	7	-3	2	260	261	286	257	210	-1	-50	132	-12	-92
	28	-22	-17	-16	-34	-65	-24	-23	-20	-13	-72	49	-8	175	33	-82	-61	-90	2	-78	-99
	29	-31	-20	-36	-44	-51	-10	-20	-6	-9	28	0	-30	105	-13	-87	-65	-86	-16	-60	-93
	30	-23	-31	-16	-25	-37	24	34	18	20	2	2	-11	12	14	-52	-14	-51	10	9	-66
C&SE	31	-30	-38	-18	3	-60	17	13	-4	209	158	-3	-20	12	79	1	-22	-32	-28	179	30
	32	16	61	8	-5	-41	33	57	17	16	28	68	119	238	-53	-85	-52	-47	25	-95	-100
	33	-33	-33	13	-41	0	18	22	178	-13	-61	-1	-51	302	-18	-100	-9	-57	360	-43	81
	34	-33	-22	-19	-65	-39	18	8	35	15	110	-1	-68	139	80	-100	-72	-93	-32	-45	-100

KEY:

Ranking colour code:			
%ch	Rank	↓	↑
0 - 10%	No ch.		
10 - 50%	Low		
50 - 100%	Medium		
> 100%	High		

For TP, comparing the results across the five regions, all except the EA policies show robustness across the geographical scale under multiple climate and/or socio-economic scenarios as shown in Tables 7.4. At the baseline, none of the polices increase timber production, suggesting that there is no robustness across the regions.

When considering the various CD scenarios, the results show that all except the EA policy have at least one CD scenario under which total TP is higher with adaptation than with no adaptation, suggesting robustness across the geographical scale. In particular, both TA and CA polices increase TP across all the five regions under 8 out of the 13 CD scenarios. The % increase in TP under the two adaptation policies is estimated 'high' (i.e., >100% relative to with no adaptation, as shown in Tables 7.4) under most of these scenarios and across most of the regions. In contrast, the BA policy is robust across the regions only under the CD-13 scenario, where TP increases by 38-308% (relative to no adaptation) across the regions. While, the effect of the environment-focussed adaptation under almost all the various climate change scenarios is opposite leading to a decline in TP, as it focusses on increasing protected forest areas that result in a reduction in wood yield for production.

Comparing the results under the different SED scenarios, TP increases with adaptation across all the regions under 6–10 of the 16 SED scenarios for all except the EA policy (Tables 7.4). Most of the % increase in TP with adaptation (particularly under the TA and CA policies) is estimated 'high' under most of the scenarios and regions. These suggest that the three policies also show robustness across the geographical scale. However, as in the case for the CD scenarios, although it remains unchanged under most of the SED scenarios, TP generally declines across all regions under the EA adaptation policy, as it focusses on maintaining/increasing forest areas, which leads to a decline in wood yield for production. Furthermore, when the four C&SED scenarios are considered, both the TA and CA policies show robustness across the regions and under two C&SED scenarios. In this case, the increase in TP is estimated by up to 570% at the European level.

When evaluating robustness of the policies with respect to uncertainty in the CD scenarios, the results illustrate that except for the CA policy (in eastern Europe) all policies do not increase TP under at least one CD scenarios in any of the geographic regions. This is also true across all the SED scenarios, without any exception to any policy/region. These results suggest that for TP there is no robustness with respect to both climate and socio-economic change uncertainty. In terms of the combined C&SED scenarios, the exceptions are for the CA policy at the European scale and in both western and eastern Europe as well as for the TA policy in southern Europe (Tables 7.3). This highlights that both the BA and EA policies are less robust to the uncertainty in the combined climate and socio-economic future changes.

Table 7.4: *The % change in TP with and without adaptation under the various CD, SED, and C&SED scenarios.*

Timber production (TP)		Behavioural					Environmental					Technological					Combined				
		Eu	W	S	E	N	Eu	W	S	E	N	Eu	W	S	E	N	Eu	W	S	E	N
BL	1	-39	-34	-17	-57	-44	-100	-100	-100	-100	-100	-7	-4	-24	-12	0	-2	0	-14	-2	0
CD	2	-56	0	804	-79	-61	-100	-100	-100	-100	-100	-3	27	337	10	-27	-11	-6	298	36	-57
	3	6	102	812	-10	-13	14	104	688	-39	35	-4	-4	109	-2	-6	9	23	252	9	2
	4	-6	38	9	-7	-41	-100	-100	-100	-100	-100	49	99	50	42	15	61	119	65	71	15
	5	-68	168	2	-85	-77	-67	-100	-87	-87	-55	-30	274	-78	8	-74	-43	244	-73	24	-93
	6	-50	125	29	-81	-48	-28	-61	-18	-70	25	-1	198	-36	-6	-29	85	343	85	25	108
	7	0	50	165	-3	-21	-100	-100	-100	-100	-100	45	164	590	22	2	38	106	345	33	10
	8	17	-24	213	2	0	-100	-100	-100	-100	0	432	527	327	4	0	635	800	365	5	0
	9	-1	-55	122	4	7	-100	-100	-100	-100	-100	133	411	800	4	8	172	554	779	7	8
	10	-70	-51	-9	-97	0	-100	-100	-100	-100	-100	309	544	805	73	256	425	800	848	114	256
	11	-2	18	355	1	-15	-100	-100	-100	-100	-100	36	72	210	53	13	-3	22	144	52	-43
	12	-83	-27	-52	-94	-80	-100	-100	-100	-100	-100	-6	65	-30	-9	-11	-5	213	-55	21	-45
	13	308	276	614	38	0	-100	-100	-100	-100	0	100	108	765	88	0	132	140	1193	126	0
	14	-30	-38	-48	-24	-31	-4	-10	32	-30	10	21	43	9	46	1	-14	-17	-26	44	-46
SED	15	31	46	19	90	5	-100	-100	-100	-100	-100	32	57	13	66	-37	38	64	23	82	7
	16	-9	-12	-23	-5	-2	-2	-4	-5	0	0	-2	0	-13	-3	0	-3	-1	-14	-3	0
	17	2	-4	-26	5	12	2	4	4	0	0	0	0	2	0	0	-1	-2	2	-1	0
	18	21	11	24	80	12	-100	-100	-100	-100	-100	-83	-97	-97	-96	-59	34	27	63	93	15
	19	24	24	-1	13	34	1	1	2	0	0	-4	-3	-2	-3	-5	-3	-3	-2	-3	-5
	20	-1	-1	-27	1	0	-4	-20	81	-2	0	24	26	190	10	4	23	26	184	9	5
	21	204	10	4	1	189	0	0	0	0	0	1081	441	115	179	347	1163	462	142	206	354
	22	183	212	147	996	49	-100	-100	-100	-100	-100	177	286	248	986	10	172	275	231	972	10
	23	4	-1	-21	5	11	0	0	0	0	0	0	-3	22	4	-2	-9	-6	-1	-7	-15
	24	0	0	0	0	0	0	0	0	0	0	153	13	4	7	129	1126	446	129	204	347
	25	726	292	64	38	330	-100	0	0	0	-100	-100	0	0	0	-100	985	400	81	158	346
	26	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	985	400	81	158	346
	27	0	0	0	0	0	0	0	0	0	0	167	19	8	9	130	1110	432	131	203	344
	28	7	47	-52	9	-3	4	-1	28	-8	8	1	73	3	13	-34	15	105	12	26	-25
	29	250	133	210	912	88	-100	-100	-100	-100	-100	284	209	456	979	55	287	215	458	971	55
	30	-6	-10	-11	-4	-1	-1	-1	-5	0	0	-1	-1	-7	0	1	-1	0	-5	-1	1
C&SE	31	-46	-53	5	-7	0	-14	-15	-7	-4	0	1	1	-4	-7	0	1	1	3	0	0
	32	0	0	0	0	0	0	0	0	0	0	52	46	5	1	0	55	48	6	1	0
	33	5	83	163	-27	-10	-5	6	-3	-6	-8	-6	8	-37	11	-2	3	14	-6	21	-11
	34	-100	0	-100	-100	0	-61	0	-100	-73	0	566	17	10	328	211	570	14	10	337	209

KEY:

Ranking colour code:			
%ch	Rank	↓	↑
0 - 10%	No ch.		
10 - 50%	Low		
50 - 100%	Medium		
> 100%	High		

Table 7.5 presents a summary of the effects of each policy and ranking of the % change in the LUD after adaptation under the various climate and socio-economic scenarios. The indicator represents multi-functionality of the European landscape with the complex interactions and associated changes in the various land uses, including urban, intensive arable, intensive grassland, extensive grassland, forest and unmanaged land. The results reflect the various trade-offs and synergies between these land use changes under the various scenarios due to adaptation. As shown in 'dark green' in Table 7.5, except the few cells with a high increase

under some of the scenarios (particularly in northern Europe with up to a 216% increase under a C&SED scenario), the % change in LUD under most of the scenarios is estimated only ranging between 'insignificant' to 'medium' across all the adaptation policies.

Although small in magnitude, all adaptation polices increase LUD across all the five regions under at least one of the scenarios. This suggests that there is robustness for all the adaptation policies across the geographical scale. Of the four, the policy with the most number of scenarios under which it shows robustness across the five regions is the EA, with two CD, five SED and two C&SED scenarios (Table 7.5). When considering the scenario groups, only BA and EA adaptation policies increases LUD across all the five regions under at least one of the CD scenarios, which suggests that the other two (TA and CA) policies are not robust with respect to geographic scale. In contrast, when the SED scenarios are considered only the TA policy does not increase LUD across the regions. Similarly, under the C&SED scenarios all except the CA policy increases LUD across all regions, showing robustness with respect to geographical scale. In terms of the robustness across the scenarios, the results suggest, with the exception for the EA policy (in northern Europe under the CD scenarios), that all of the adaptation policies are not robust with respect to the uncertainty regarding the future climate and socio-economic changes.

Table 7.5: *The % change in LUD with and without adaptation under the various CD, SED, and C&SED scenarios.*

		Land use diversity (LUD)																			
		Behavioural adaptation					Environmental					Technological					Combined adaptation				
		Eu	W	S	E	N	Eu	W	S	E	N	Eu	W	S	E	N	Eu	W	S	E	N
BL	1	-3	4	1	-8	-11	-2	-7	-10	-9	21	-14	-4	-6	-14	-37	-19	-23	-9	-20	-21
CD	2	-12	-9	-19	-17	-1	11	2	6	-10	69	-18	-11	-21	-15	-34	-10	-22	-6	-21	22
	3	15	5	10	-9	79	8	7	-1	0	39	-21	-24	-18	-26	-9	-34	-51	-30	-27	-20
	4	-5	-1	-3	-1	-14	-9	-11	-10	-18	3	-15	-4	-7	-13	-42	-21	-19	-13	-21	-31
	5	-17	1	-28	-29	-23	11	3	8	-11	70	-15	-7	-20	-8	-54	-50	-53	-55	-31	-68
	6	19	5	22	-5	103	28	2	29	6	148	-19	-25	-23	-1	-29	-33	-49	-48	-19	11
	7	12	3	11	-4	60	4	-9	-13	-18	97	-4	-6	-4	-5	2	0	-8	4	-11	30
	8	-10	4	-2	-11	-45	4	1	1	-6	23	-24	-3	-20	-21	-69	-55	-36	-53	-60	-85
	9	-10	7	-8	-4	-48	6	3	0	1	24	-20	-1	-19	-16	-58	-25	-10	-23	-15	-61
	10	-22	-3	-32	-7	-61	8	2	-2	-3	47	-17	-1	-17	-10	-56	-46	-27	-54	-48	-70
	11	9	-6	7	-8	77	6	-7	-15	-18	114	-8	-16	-9	-3	1	-2	-21	-2	-14	61
	12	-17	-2	-22	-35	-20	12	-5	3	-8	89	-10	-2	-16	-4	-28	-48	-57	-45	-27	-59
	13	-11	-4	-4	-13	-44	7	-10	-2	-11	107	-16	-8	-13	-17	-45	-54	-48	-53	-54	-76
	14	24	12	16	6	106	10	8	16	-1	24	-1	3	-4	-7	9	-43	-56	-44	-39	-18
SED	15	-4	7	4	-6	-23	-7	-11	-8	-17	9	-6	-2	0	-10	-44	-19	-16	-4	-20	-35
	16	9	-2	15	4	35	8	7	9	13	1	-13	-21	-11	-8	-4	-4	-20	10	1	7
	17	-8	-8	-16	-6	-2	6	1	16	5	1	0	-5	5	3	-2	61	45	67	49	89
	18	-1	2	3	-1	-9	-13	-20	-13	-24	9	-12	-16	-14	-22	5	-17	-21	-9	-25	-12
	19	-5	-2	-18	-1	1	6	-2	21	7	1	-2	-10	1	8	-5	-3	-11	4	3	-5
	20	-11	-11	-16	-15	-1	5	-3	14	10	6	-21	-33	-19	-12	-6	-1	-25	6	-2	49
	21	-12	-3	0	8	-44	1	3	3	3	-3	-2	12	3	19	-34	-14	-15	-11	5	-28
	22	-9	6	-12	6	-38	-3	-3	-9	-1	3	-25	-13	-18	-22	-51	-16	-22	-12	-17	-11
	23	-9	-8	-17	-10	-2	8	3	15	17	1	-4	-11	-8	12	-4	-13	-19	-13	-3	-14
	24	-3	1	0	-2	-14	2	4	3	2	-2	0	-1	-7	9	3	-3	-1	-1	10	-16
	25	-1	17	9	28	-50	-1	-5	0	8	-4	-7	-7	-9	-18	2	-15	-7	1	-2	-48
	26	0	-1	0	5	-3	13	15	5	24	10	5	6	-8	-3	21	-5	7	2	15	-38
	27	-7	-5	-3	-2	-15	-3	-6	-5	2	0	2	-1	-6	9	8	-4	-7	-2	5	-11
	28	-11	-2	-15	-18	-15	1	3	2	-3	1	-25	-23	-17	-33	-31	-46	-49	-47	-54	-28
	29	-8	5	-12	11	-38	3	-1	-4	0	19	-24	-14	-18	-20	-49	-16	-21	-11	-13	-16
	30	5	1	11	3	5	9	14	6	9	2	2	5	-2	2	0	14	0	12	7	56
C&SE	31	16	4	11	81	31	24	12	13	104	45	8	2	7	35	21	-3	-13	-13	81	-6
	32	-19	3	-15	-9	-62	-3	-2	-3	-6	-1	-42	-15	-28	-60	-81	-70	-56	-64	-77	-88
	33	-4	4	-11	-22	22	10	11	53	-2	-2	4	-5	72	-9	-4	47	31	145	-6	105
	34	-20	-8	-23	-32	-28	29	1	11	7	216	-35	-55	-35	-12	-18	-60	-69	-72	-51	-19

KEY:			
Ranking colour code:			
%ch	Rank	↓	↑
0 - 10%	No ch.		
10 - 50%	Low		
50 - 100%	Medium		
> 100%	High		

Water resources and use: Water exploitation index

Table 7.6 presents a summary of the benefits of adaptation with a ranking of the percentage change in WEI with respect to no adaptation both at the baseline and under the various climate and socio-economic scenarios. In contrast, WEI shows the highest number of scenarios (than other sectors/sub-systems) under which three of the four adaptation policies (i.e., BA, TA and CA) reduce WEI across all the five regions in at least half of the 34 scenarios considered. The EA policy also reduces WEI across all the regions under 9 of the 34 scenarios. These results suggest that there is robustness with respect to the geographic regions under all the adaptation policies. However, unlike for other sectors/sub-systems (e.g., FP and TP) the highest % change (i.e., reduction in WEI) across all the scenarios is estimated only at medium level, with the highest being less than 100% reduction in water stress with respect to the impact with no adaptation (Table 7.6).

When focussing on the CD scenarios, BA followed by CA are the most robust policies across the geographic scale, reducing WEI (by up to 35% and 100%, respectively, both in eastern Europe) under all except three of the 13 CD scenarios considered. Similarly, the TA and EA policies reduce WEI across all the five regions in 8 (by up to 62% in northern Europe) and 7 (by up to 100% in eastern Europe), respectively, of the 13 CD scenarios, suggesting robustness across the geographical scale.

In contrast, comparison of the results under the different SED scenarios suggest that EA is the only policy that does not improve water stress across the regions under any of the 16 SED scenarios (Table 7.6). However, both CA and BA policies show the highest robustness with respect to the geographic scale by reducing WEI across all the five regions under all except two of the 16 SED scenarios considered. In terms of the magnitudes of change, all except the EA policy reduce WEI by more than 50% across two/more of the regions under at least one of the SED scenarios, although the highest reduction in WEI due to adaptation is less than 80% across all regions and SED scenarios. However, when the combined extreme C&SED scenarios are considered, all adaptation policies also show robustness with respect to the geographical scale, by reducing WEI across all the five regions under at least one of the four C&SED scenarios. The magnitudes of reduction in WEI due to adaptation are estimated between 1% (under the BA policy) and 99.8% (under the CA policy) across all the scenarios and regions.

When evaluating robustness across the scenarios, the results demonstrate that, more than any of the other sectors/sub-systems considered, all (except the EA) adaptation policies reduce WEI across all the CD and/or SED and/or C&SED scenarios in at least two of the five regions. For example, the CA policy reduces WEI across all the CD, SED, and C&SED scenarios both at the European level and in the western and northern Europe. Similarly, the TA policy reduces WEI across all the CD, SED and C&SED scenarios in western and northern Europe, as well as at the European scale across all the SED scenarios. In contrast, the BA adaptation policy reduces

WEI in the western, eastern and northern regions across all the CD scenarios, while reducing in eastern and northern Europe across the C&SED scenarios. Therefore, these results suggest that there is a significant robustness in terms of benefits of the adaptation policies for the water sector/sub-system with respect to the uncertainty in future changes of both the climate and socio-economic scenarios.

Table 7.6: *The % change in WEI with and without adaptation under the various CD, SED, and C&SED scenarios.*

Water exploitation index (WEI)		Behavioural					Environmental					Technological					Combined				
		Eu	W	S	E	N	Eu	W	S	E	N	Eu	W	S	E	N	Eu	W	S	E	N
BL	1	-4	-11	7	-8	-17	44	6	81	58	2	3	-34	28	37	-51	-12	-37	0	17	-54
CD	2	-12	-11	-7	-19	-14	-5	18	11	-44	-8	-24	-32	-23	-14	-52	-48	-40	-37	-66	-69
CD	3	15	-11	87	-13	-17	53	1	156	39	0	17	-36	109	19	-51	-10	-38	41	-10	-54
CD	4	-8	-10	-6	-7	-17	37	20	46	55	9	1	-24	11	32	-51	-14	-33	0	0	-54
CD	5	-24	-19	-20	-35	-18	-59	-48	-41	-91	-44	-32	-40	-22	-37	-3	-76	-73	-62	-94	-84
CD	6	-12	-8	-13	-14	-17	-54	-45	-40	-88	-57	-29	-40	-27	-17	-50	-73	-72	-62	-92	-84
CD	7	-7	-11	2	-15	-17	114	11	182	181	0	-15	-35	-8	11	-51	-28	-37	-30	-4	-54
CD	8	-9	-8	-9	-9	-28	-89	-93	-80	-99	-41	-30	-42	-27	-19	-55	-93	-95	-84	-100	-87
CD	9	-10	-11	-7	-12	-34	-90	-94	-80	-100	-46	-29	-35	-26	-23	-59	-93	-96	-84	-100	-88
CD	10	-10	-14	-7	-5	-33	-90	-95	-79	-100	-38	-27	-40	-18	-17	-62	-93	-97	-84	-100	-89
CD	11	-15	-11	-16	-19	-17	122	4	264	171	0	-6	-36	36	-1	-51	-11	-37	27	-9	-54
CD	12	-22	-28	-4	-33	-21	-91	-95	-83	-100	-30	-35	-50	-19	-32	-53	-93	-97	-83	-100	-84
CD	13	-12	-10	-12	-15	-16	-80	-85	-63	-100	-68	-24	-38	-21	-11	-52	-86	-91	-71	-100	-85
CD	14	-9	-9	3	-21	-17	13	2	15	26	0	-1	-34	12	33	-51	-24	-39	-19	-8	-54
SED	15	-13	-15	-9	-15	-22	82	38	114	112	7	-7	-38	4	30	0	-16	-39	-1	0	-58
SED	16	-11	-11	-10	-11	-17	9	0	22	8	0	-15	-36	2	1	-51	-12	-36	6	9	-54
SED	17	-14	-7	-15	-22	-10	5	0	5	13	0	-23	-32	-29	2	-46	-26	-33	-27	-15	-48
SED	18	-8	-13	-4	-9	-21	36	53	37	22	9	-12	-32	-6	2	-55	-42	-44	-34	-48	-59
SED	19	-12	-7	-8	-27	-10	10	1	17	9	0	-20	-32	-31	17	-46	-25	-33	-24	-12	-48
SED	20	-9	-9	-8	-10	-14	13	0	36	7	0	-11	-34	11	10	-49	-7	-35	18	20	-51
SED	21	-54	-29	-54	-72	-31	-6	11	-9	-18	32	-49	-46	-47	-51	-59	-62	-49	-66	-67	-61
SED	22	-18	-8	-18	-26	-11	47	65	56	20	16	-18	-33	-11	-12	-47	-45	-37	-47	-49	-49
SED	23	-18	-7	-18	-32	-10	19	7	23	31	0	-17	-32	-31	40	-46	-28	-33	-29	-13	-48
SED	24	-19	-25	-18	-14	-15	-26	-14	-26	-41	2	-52	-65	-40	-50	-78	-67	-70	-58	-74	-79
SED	25	-21	-14	-17	-33	-20	22	12	18	32	84	-4	-33	1	24	-53	-40	-38	-42	-38	-55
SED	26	8	-6	10	18	6	12	5	12	19	21	-13	-36	-8	7	-63	-46	-40	-47	-46	-65
SED	27	12	12	14	12	-3	9	30	16	-19	18	-37	-52	-21	-38	-75	-58	-64	-43	-68	-78
SED	28	-18	-10	-21	-20	-8	-5	9	-9	-12	8	-29	-40	-24	-29	-54	-58	-56	-58	-60	-55
SED	29	-21	-8	-18	-39	-10	56	63	74	27	18	-13	-31	-5	-3	-46	-41	-35	-46	-40	-48
SED	30	-15	-16	-11	-21	-22	4	5	12	-11	0	-23	-39	-19	-12	-54	-33	-42	-23	-39	-58
C&SE	31	-16	-18	-10	-22	-22	-79	-85	-62	-99	-68	-29	-40	-22	-22	-55	-86	-92	-74	-100	-86
C&SE	32	6	-2	27	-1	-17	-79	-86	-48	-99	-64	-22	-39	18	-33	-58	-84	-91	-57	-100	-86
C&SE	33	-15	-17	1	-23	-22	36	13	72	37	3	2	-44	42	25	0	-13	-51	51	-13	-58
C&SE	34	6	5	27	-13	-11	147	87	138	263	187	18	-49	41	127	-62	-28	-52	-25	17	-64

KEY:

Ranking colour code:			
%ch	Rank	↑	↓
0 - 10%	No ch.		
10 - 50%	Low		
50 - 100%	Medium		
> 100%	High		

Biodiversity: Biodiversity vulnerability index

Table 7.7 shows the effect of the four adaptation policies summarising ranking of the % change in BVI across the various scenarios. Following the urban sector/sub-system, the effect of all the adaptation policies on BVI is 'low' in comparison with other sectors/sub-systems, with the changes with respect to no adaptation estimated less than 50% (increase/decrease) across all the scenarios and regions. Although small in magnitude, as in other sectors/sub-systems, the results (in terms of directions of change) also demonstrate that there is robustness with respect to the geographical scale under all the adaptation policies, which reduces BVI across all the five regions under at least one of the various CD, SED, and C&SED scenarios.

When considering the CD scenarios, only the EA policy shows robustness across the geographical scale, which reduces BVI by up to 23% under nine of the 13 CD scenarios. However, the results show that the other three adaptation policies have a knock-on effect on biodiversity, although relatively small in magnitude when compared with other sectors/sub-systems. Particularly the CA policy shows a significant and widespread negative effect across almost all of the CD scenarios and regions, which increases vulnerability by up to 29% higher than that of with no adaptation.

In contrast, while the magnitudes are generally small, a comparison of the results across the different SED scenarios suggest that there is robustness with respect to the geographical scale as all the adaptation policies reduce BVI across the five regions under at least one of the SED scenarios (Table 7.7). The EA and TA policies, in particular, show the highest robustness as they reduce BVI across all the five regions under the ten and five of the 16 SED scenarios, respectively. The highest % reduction in BVI under the various SED scenarios is estimated at 24% in eastern Europe under the TA policy. However, when the C&SED scenarios are considered, only EA and TA policies show robustness with respect to the geographical scale, by reducing BVI across all the five regions under at least one of the four C&SED scenarios. The EA in particular is more robust under three out of the four C&SED scenarios, reducing BVI across all the five regions by up to 31% (e.g., in northern Europe). In contrast, the other two (BA and CA) policies increase BVI by up to 24%, relative to those with no adaptation, illustrating the trade-offs and negative effects of the policies on biodiversity. However, when evaluating robustness across the scenarios, except for the EA policy under the C&SED scenarios where BVI reduces across all C&SED scenarios, the results demonstrate that for BVI all adaptation policies are less robust with respect to the uncertainty across future climate and socio-economic changes.

Table 7.7: *The % change in BVI with and without adaptation under the various CD, SED, and C&SED scenarios.*

		Biodiversity vulnerability index (BVI)																			
		Behavioural					Environmental					Technological					Combined				
		Eu	W	S	E	N	Eu	W	S	E	N	Eu	W	S	E	N	Eu	W	S	E	N
BL	1	5	4	5	11	2	-2	0	-3	-1	-4	6	9	4	10	2	13	20	15	17	3
CD	2	5	6	10	12	-2	-5	-8	-7	-4	-3	9	8	10	5	12	12	14	17	19	4
	3	0	0	1	5	-2	-10	-13	-8	-9	-8	10	16	12	8	4	17	29	28	11	4
	4	8	4	6	6	13	4	0	-4	1	16	10	4	4	8	21	19	17	13	20	22
	5	9	6	11	15	8	-7	-3	-6	-4	-13	13	12	11	6	23	24	28	25	18	23
	6	1	3	3	6	-5	-14	-5	-12	-15	-23	6	11	8	-5	8	11	24	21	7	-5
	7	2	0	1	8	0	-7	-10	-4	-4	-8	2	5	3	2	0	9	12	17	11	0
	8	8	2	4	12	14	-4	-1	2	0	-12	15	8	8	13	27	26	22	24	29	29
	9	9	3	6	12	13	-5	0	3	-1	-16	9	6	6	9	14	12	12	9	12	15
	10	9	4	8	7	16	-6	1	3	0	-22	9	6	5	7	14	21	20	23	23	19
	11	2	3	4	9	-2	-8	-11	-4	-4	-10	5	11	7	2	0	7	11	14	11	-2
	12	8	2	8	12	10	-8	-1	-4	-9	-16	5	0	4	0	12	22	28	18	14	24
	13	5	3	5	10	3	-4	-2	-2	-10	-5	6	9	6	2	4	19	28	28	21	6
	14	-1	-1	-1	4	-4	-9	-9	-7	-7	-11	3	5	3	5	-1	15	20	19	21	3
SED	15	3	1	5	7	2	-2	-1	-1	-1	-4	4	6	3	6	3	11	16	9	16	4
	16	1	2	1	1	1	-5	-6	-10	-7	0	5	11	3	2	1	4	11	1	1	1
	17	2	2	6	3	0	-2	-1	-7	-2	0	-1	1	-6	-2	0	-10	-12	-12	-12	-6
	18	2	3	3	2	1	0	2	-2	1	-2	3	6	-2	6	2	11	17	7	19	4
	19	1	2	5	0	-2	-3	0	-11	-3	0	0	4	-4	-4	1	1	5	-4	-1	1
	20	6	6	9	10	0	-5	-3	-11	-10	-1	10	22	11	5	2	9	20	9	5	2
	21	-3	-2	-2	-4	-3	-3	-3	0	0	-6	-2	0	1	-4	-4	9	16	23	7	-3
	22	0	-3	9	-1	-2	-3	-3	-1	-7	-3	12	16	12	17	6	16	19	30	21	2
	23	3	3	8	4	0	-4	-2	-11	-7	0	1	4	2	-5	1	4	7	6	-1	4
	24	2	1	1	4	3	-3	-3	0	0	-7	-7	-2	-3	-10	-11	1	8	6	1	-8
	25	-4	-6	2	-4	-6	-1	-2	7	12	-12	-1	-2	0	-1	-2	5	9	11	10	-5
	26	-1	0	0	-1	-2	-9	-6	-1	-10	-15	-11	-6	-8	-24	-11	-5	4	3	-13	-14
	27	-1	-1	0	-1	-1	-7	-5	-1	-7	-11	-7	-2	-1	-8	-14	2	10	8	5	-11
	28	5	2	8	9	4	1	-1	-1	1	3	15	19	9	19	12	28	36	39	35	10
	29	0	-2	11	-1	-5	-5	-3	-1	-7	-8	11	17	14	16	2	14	19	31	18	-3
	30	1	-1	2	3	1	-5	-8	-7	-5	0	-2	-2	-5	-1	0	-1	0	-6	-1	1
C&SE	31	1	3	6	-5	0	-6	-8	-4	-15	-2	-3	-2	-4	-9	0	-1	4	5	-17	0
	32	2	-3	2	10	2	-3	-4	-1	-5	-1	15	13	11	34	9	27	29	37	47	9
	33	0	0	-1	15	-7	-4	-5	-14	0	1	-3	0	-22	2	2	-8	-4	-28	3	-5
	34	12	6	7	24	13	-19	-9	-15	-20	-31	10	27	11	1	-2	20	33	32	23	-2

KEY:

Ranking colour code:			
%ch	Rank	↑	↓
0 - 10%	No ch.		
10 - 50%	Low		
50 - 100%	Medium		
> 100%	High		

In summary, the sensitivity (Chapter 5) and scenario (Chapter 6) analyses have illustrated that while there are some consistent directions and patterns in sensitivity of future impacts under some scenarios, there are significant uncertainties in future impacts across sectors/sub-systems and scales and the various scenarios. Hence, long-term adaptation planning needs to take a holistic approach in order to address these uncertainties, while at the same time improving on important synergies and reducing trade-offs between different adaptations across sectors/sub-systems, scales, and scenarios. The following sub-section presents the nexus-based conceptual framework developed followed by the ODAT, MDAT and RAAP analyses and a review of IA modelling approaches. The framework provides an important platform for informing long-term, multi- and cross-sectoral adaptation planning for the food-water-land-ecosystems (FWLE) nexus.

7.3.3 A framework for long-term adaptation planning: A nexus approach

Many of the earth's natural resources are declining and their unsustainable exploitation leads to an increasing stress on global ecosystems. As environmental change and degradation continue the need for interdisciplinary research to develop new integrated approaches for a more sustainable use of these resources is crucial. The quantitative analysis of Europe's FWLE nexus highlighted the strong interdependences between the food, water and land resources use and environmental ecosystems that provide vital support for human wellbeing and health of the natural systems. The complex interactions and interdependencies analysed here also highlighted the underlying direct and indirect implications of future drivers of change within and across the systems (i.e., climatic or non-climatic factors), the environmental pressures they create (e.g., flooding, loss of biodiversity), and the resulting impacts (e.g., competition for land and water) under changing conditions. Adapting to future changes in climate and socio-economic drivers require a holistic understanding of these interactions and associated synergies, conflicts and trade-offs in order to devise appropriate integrated adaptation policies and sustainable resources management strategies across the sectors/sub-systems and regions. This necessitates a systems integration approach and coordinated policymaking effort across the nexus sectors/sub-systems. However, Liu *et al*. (2015) highlighted that while these various coupled human and natural systems and associated sustainability challenges are closely intertwined as also demonstrated in this study; they are often studied and managed separately, potentially risking important trade-offs and conflicts as well as overlooking potential synergies between competing systems. In addition, the lack of understanding of systems interactions also have important implications on the effectiveness of adaptation measures in reducing future impacts, as measures aimed at specific targets may have the potential to generate indirect pressures on other efforts, such as preserving or enhancing environmental quality (Fezzi *et al*. 2015).

The lack of a holistic information for decision-makers on such complex nexus interactions calls for the development and quantification of integrated frameworks to address these challenges by focussing on the question of what hinders integrated adaptation planning at scales appropriate for policymaking on cross-sectoral adaptation. Hence, the use of the nexus approach can help inform some key characteristics of integrated adaptation decision-making on cross-sectoral impacts of future changing conditions, including (e.g., Eisenack 2012): (i) *Uncertainty*: as the nature and magnitude of future impacts are highly uncertain due to various factors as discussed earlier, (ii) *Spatial diversity*: as the biophysical and socio-political-economic conditions vary spatially, and hence the potential impacts differ strongly across different regions, even between adjacent areas, (iii) *Biophysical complexity*: as various components of a system even in single regions are affected in different ways and magnitudes, and (iv) *Social, political, and economic settings*: as various systems are also interlinked in different ways in such a way that some adaptations affect multiple different sectors/sub-systems differently with important trade-offs between sectors/sub-systems. For achieving such adaptation to climate change by integrating the various human and environmental systems, the development and quantification of appropriate conceptual frameworks is crucial. Drawing from the systematic and extensive application of the CLIMSAVE integrated methodology combined with a review of the literature, a new nexus-based conceptual framework has been developed based on a system-of-systems integration approach. The framework provides an important platform in order to inform the development of a long-term and multi-/cross-sectoral planning and robust decision-making on adaptation (Figure 7.2).

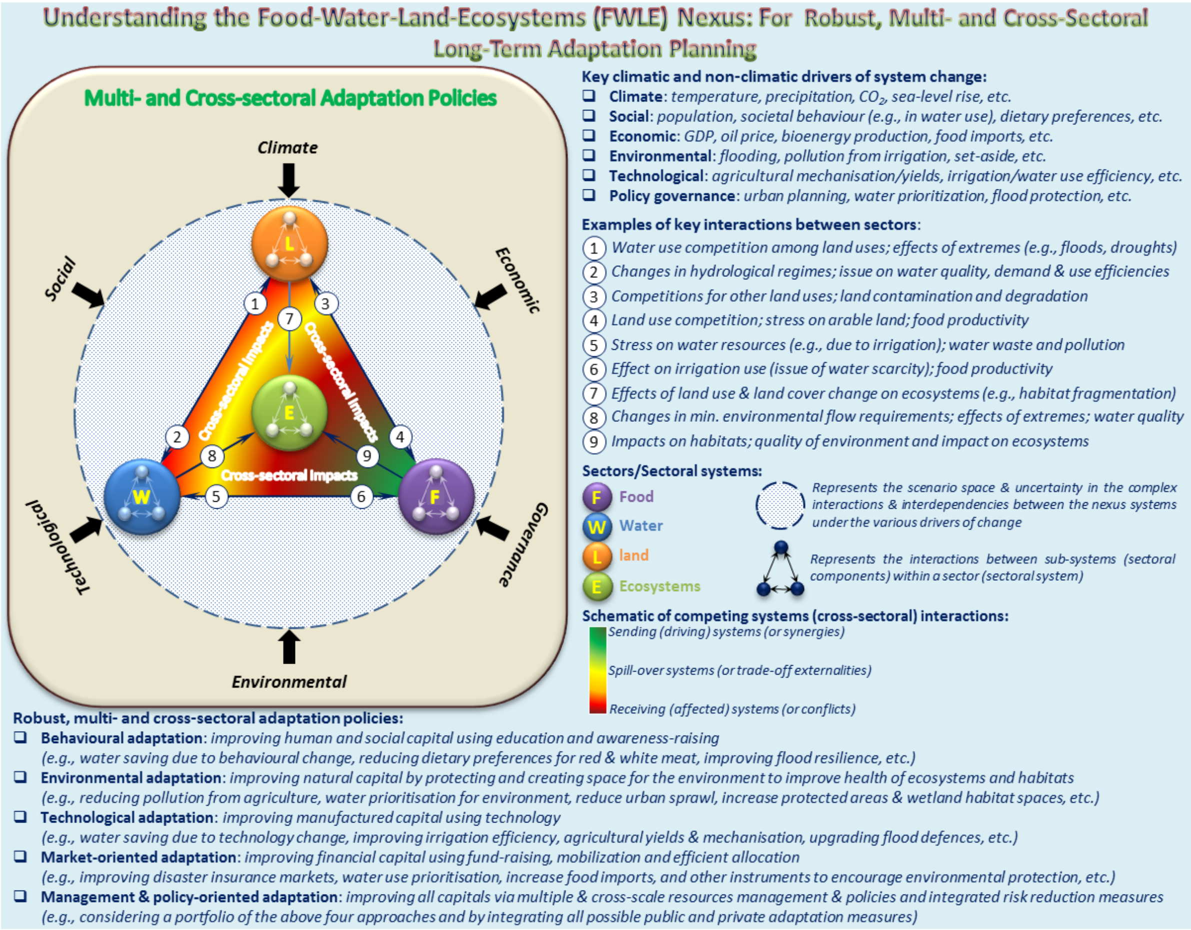


Figure 7.2: *A nexus-based conceptual framework for long-term, multi- and cross-sectoral adaptation planning.*

Various studies have already identified key connections in the socio-ecological systems, which clearly show that healthy and robust ecosystems are an important prerequisite to meeting some of the most essential goals of future development and human wellbeing (e.g., Diaz *et al*. 2006; Cardinale *et al*. 2012; Larigauderie *et al*. 2012; Dearing *et al*. 2014; Howe *et al*. 2014; Bennet *et al*. 2015; Pinter *et al*. 2015). Therefore, protecting their integrity is of fundamental importance for human wellbeing (Ringler *et al*. 2013). In addition, management of socio-ecological systems requires a holistic understanding of the highly diverse spatial (e.g., local to regional) and temporal (e.g., short- to long-term) conditions across the various systems (Eisenack 2012). As such, these issues also demonstrate the need for understanding the interdependencies and potential synergies and trade-offs between the bio-physical, socio-economic and environmental systems across the nexus between various sectors/sub-systems and scales when planning for long-term adaptation. However, most previous nexus study frameworks either (i) do not take into account ecosystems and/or environmental conditions (e.g., the commonly considered water-food-energy nexus; Bazilian *et al*. 2011; Rasul and Sharma 2015, or water-energy nexus; Hussey and Pittock 2012), or (ii) with limited treatment of interactions as there is often an implicit focus on one or more sectors/sub-systems of the nexus (e.g., water, or food, or energy) (Granit and Lindström 2009), and (iii) still focus on a qualitative representation of the interdependence between sectors/sub-systems from the perspective of resource use without taking account of the quantitative effects of external (direct and indirect) drivers (Ringler *et al*. 2013). Hence, unlike these previous frameworks, this new integrated framework (i) puts natural ecosystems at the centre of the nexus, and (ii) takes into account the effects of future climate and socio-economic drivers. This is crucial for informing the development of robust, multi- and cross-sectoral adaptation policies that reflect the need for both a balanced management and efficient use of resources and environmental risk management for a sustainable and climate-resilient socio-economic development. In this context, the framework particularly focusses on conceptualizing the following five key hierarchical questions as detailed in Figure 7.2: (i) What are the main sectoral systems that represent the human-nature nexus? (ii) What are the key drivers of change in the nexus systems? (iii) Which indicators/metrics of cross-sectoral impacts and adaptation are more relevant for stakeholders? (iv) Which interactions between (within and across) the nexus systems are more important? (v) How robust are the multi-/cross-sectoral adaptation policies across the sectors/sub-systems, scales, and scenarios? Quantification of the framework will help address these questions, by focusing on key aspects of the coupled human-environment systems for understanding the interdependencies of and potential synergies, conflicts and trade-offs between the nexus systems under changing conditions. As such, this will provide decision-makers with improved information on the response of the nexus systems across scales in order to devise robust multi- and cross-sectoral adaptation policies, which help maximize benefits and minimize unintended negative consequences.

7.4 The CLIMSAVE IAP: Key Features and Potential Improvements

The CLIMSAVE integrated framework emphasizes on the fact that European land, water and food resources and biodiversity & ecosystem services are highly intertwined with complex cross-sectoral interactions resulting in (conflicting and/or complementing) competitions for water and land with associated indirect impacts across the sectors/sub-systems and scales. Hence, any assessment of the use and management of these resources and how their interactions shape Europe's future landscape change dynamics require an integrated analysis and modelling approaches. The CLIMSAVE IAP adopted a systems integration approach based on coupling of ten disparate sectoral meta-models. The modelling approach takes into account the key linkages and interactions between six different European land- and water-based sectors/sub-systems (i.e., agriculture, biodiversity, coasts, forest, urban, and water) representing the coupled human-environment systems in the region, which are captured through appropriate process-based data exchange between the various models integrated within the common platform (i.e., the CLIMSAVE IAP; see Section 3.3). A particular focus is given to identifying key points (linkages) through which the various sectors/sub-systems interact, reflecting the important competitions for land and water in order to understand the interdependence between the sectors/sub-systems through estimating, for example: (i) the urban and rural land use distributions and allocations and associated future food security issues, (ii) the water required for various uses including drinking, food production, domestic/industrial, environmental and energy use, and associated future water security issues, (iii) the potential environmental risks (e.g., flooding, drought, loss of habitats, etc.), as well as (iv) the implications of the socio-ecological footprint of these interactions for biodiversity and ecosystem services.

In this context, as a first initiative of its type at the European scale, the CLIMSAVE integrated methodology and assessment platform is novel in understanding future landscape change dynamics at a continental or large area scale by taking into account the potential impacts of both climate and socio-economic change drivers and associated future scenarios (Harrison *et al*. 2012). However, as the IAP represents a complex network of these various interlinked sectoral models, identifying the key relationships between the various driver variables and output parameters (representing the various impacts and adaptation indicators/metrics) requires a careful exploration of the results, particularly when summarised across multiple sectors/sub-systems and across different spatial scales. Consequently, while CLIMSAVE provides important contribution to the field through advancing current knowledge in a number of ways (e.g., outlined in Sections 3.1 and 3.2), as is the case with other similar integrated studies of such complex scientific and policy problems there are some limitations in terms of methodology and use. This analysis has identified the key areas of potential future improvements specifically on the CLIMSAVE integrated methodology approach and the tool as well as on integrated modelling frameworks more generally. The following sub-section discusses these key features (strengths) and potential improvements (current limitations) of CLIMSAVE's overall integrated modelling framework and its assessment platform, as well as that of the individual sectoral meta-models integrated within the platform. The discussion broadly focusses on and structured in the context of the key factors identified as important criteria (outlined in Section 2.4.2) that need to be taken into account for: (i) selecting appropriate IAMs and/or evaluating their relevance for particular policy objectives (i.e., regional adaptation to cross-sectoral impacts), and (ii) informing development of the next generation of IAMs.

7.4.1 Key features

As highlighted in Sections 3.1 and 3.2, the key features (strengths) of the CLIMSAVE IAP lies in its holistic methodological framework which improves on previous studies in a number of ways. These include: (1) greater consideration of important cross-sectoral linkages and interactions between various sectors/sub-systems, (2) a wider application of the multi-models coupling (integration) approach, (3) improved integration of knowledge between stakeholders and scientists, (4) holistic consideration of the combined effects of both climatic and socio-economic factors, (5) multi-scale applications, (6) explicit treatment of adaptation, (7) improved flexibility, particularly in terms of treatment of uncertainty and capability for supporting sensitivity analysis, (8) user-friendly design of its user interface, and (9) improved accessibility by end users through its freely available web-based platform. These specific strengths and capabilities of CLIMSAVE's integrated methodology and the platform are discussed as below. It is worth stating that some of the advancements of the IAP over previous works are the novelty of methods implemented in the IAP and others are in terms of the scale of their application (e.g., extending locally applied methods to a regional/national and continental scale in Europe as a first initiative).

Integrating multiple sectors/sub-systems and indicators

Unlike previous landscape change IAMs which focus on limited number of sectors/sub-systems (see Appendix A), the CLIMSAVE IAP advances current practices by considering important linkages and interactions between six key land- and water-based sectors/sub-systems: agriculture, biodiversity, coasts, forestry, urban areas, and water resources. As such, the linking of various sectoral models in one platform provides stakeholders with a comprehensive and improved insight on the interactions between the various sectors/sub-systems and how this could affect future landscape change dynamics under changing conditions. In addition, the CLIMSAVE IAP also provides a large number of sectoral outputs representing the social, economic, and environmental metrics or indicators of impacts of and adaptation and vulnerability to future changes in climate as well as the social, economic, technological, environmental, and policy governance settings. As such, it allows stakeholders to explore and understand the interactions between the various sectors/sub-systems (as well as the various indicators within a sector/sub-system) across different scales, rather than focussing on a particular sector/sub-system (or sectoral indicator) and/or region, in order to devise appropriate integrated response strategies for reducing potential future impacts across sectors/sub-systems and regions.

Systems integration modelling approach

Another important feature of the CLIMSAVE platform is the fact that its integrated modelling methodology is based on multi-models coupling approach for systems integration. The modelling framework systematically integrates a range of contrasting and independent sectoral models and/or modelling approaches (such as look-up tables, statistical approaches, and optimization and process-based models). It has been argued that multicomponent models coupling approach has a significant advantage over other integrated modelling approaches (Sections 2.2) in terms of two key aspects of system-of-systems integration: (i) incorporating very detailed representations of systems and sub-system components and their connections, and (ii) allowing more depth in the representation of important individual components of a system depending on the time and other resources available for developing and running the models (Letcher *et al*. 2013). Consequently, the development of the IAP based on multiple models coupling approach provided an improved compromise between models complexity and runtime through the use of meta-modelling approach. In addition, it provided an important high flexibility over other approaches in terms of, for example, being able to: (i) independently test and validate individual models, and (ii) be able to replace and/or upgrade individual sectoral models or model components as needed when new methods and/or additional information and new datasets become available in the future.

Integrating stakeholders' knowledge

Stakeholder participation in integrated research projects is an important component in developing research outputs that are scientifically sound and relevant to political and societal decision-making, and conducive to practical application (e.g., Salter *et al*. 2010). In this context, another key feature of the design and testing and refinement of the functionality of the user interface of the IAP is its improved integration of knowledge between stakeholders and scientists. This integration was made possible using a systematic and continuous engagement with stakeholders as part of the socio-economic scenarios development process from the start to finish of the project. The CLIMSAVE project developed and implemented a new innovative scenario development framework, the Stakeholder Integrated Research (STIR) approach (Gramberger *et al*. 2015), which follows the so-called story-and-simulation approach (Kok *et al.* 2015), and ensures active participation of stakeholders throughout the project period. The new approach provided a comprehensive and structured method, which addresses important stakeholder engagement challenges ranging from appropriate selection of stakeholders to overcoming stakeholder fatigue through the process and to dealing with the time constraint for adequate stakeholder engagement throughout the research process. In order to achieve this, the CLIMSAVE project implemented a series of professionally structured and facilitated high level stakeholders' workshops applied both at the European (three workshops) and regional (Scotland, three workshops) scales. As such, it provided an improved and iterative exchange of knowledge between stakeholders and scientific experts, improving the stakeholder-science data translation process and ensuring that stakeholder perspectives are an essential component of the integrated research process.

Integrating biophysical and socio-economic variables

Another important feature of the CLIMSAVE integrated approach in terms of advancing current practice is its holistic framework. In addition to its focus on cross-sectoral integration, the framework also emphasises on a holistic treatment of both climate change and socio-economic change drivers both at the regional (Scotland) and continental (Europe) scales. This holistic view combined with the highly flexible design of the interface with slider bars/buttons/drop-down menus-based representation of the uncertainty of the various climatic and socio-economic drivers provides a number of important features. These include in terms of: (i) understanding the combined cross-sectoral effects of both climatic and socio-economic factors, and (ii) providing important flexibility to conduct sensitivity and uncertainty analysis of individual or combined drivers of climate scenarios only, socio-economic scenarios only or combined climatic and socio-economic scenarios. This allows a crucial flexibility to exploring the full scenario space, which provides a better understanding of uncertainty of future cross-sectoral impacts and adaptation needs.

Multi-scale application

Another key aspect of the CLIMSAVE IAP is its multi-scale application to assist stakeholders in developing their capacity to address impacts of climate change at continental scale (Europe), national scale (Scotland), and regional scale (sub-continental and sub-national). The selection of the spatial resolution of the IAP was based on a compromise between the scale of available harmonised input datasets, spatial detail of the output parameters, and associated model run-time (Harrison *et al*. 2013). Therefore, the European scale IAP operates at a 10 x 10 arc minute grid resolution with a total of 23,871 grid cells in Europe, while the regional scale IAP developed for Scotland operates at a 5km x 5km grid resolution, with a total of 3,472 grid cells in Scotland. Note that in this research, only results of the European IAP application are presented).

Explicit treatment of adaptation

As part of the main objectives of climate change impacts assessment studies in informing the climate change adaptation policy agenda, an explicit treatment of adaptation in IAMs is identified as crucial (e.g., Patt *et al*. 2010). However, most integrated impacts assessment studies so far either do not take into account adaptation as a whole (focussing on impacts only or mitigation only) or include it implicitly (e.g., in damage cost estimates). The CLIMSAVE integrated methodology recognised this limitation and developed a framework that improves on the treatment of adaptation in current approaches by making it an explicit control variable. This allows users to explore the cross-sectoral effects of adaptation by taking into account various adaptation strategies. As such, the 'Adaptation' and 'Cost-effectiveness' screens of the CLIMSAVE IAP's user interface provides the platform which enables uncertainties to be investigated in order to highlight the cross-sectoral benefits and conflicts and associated cost-effectiveness of different adaptation options to better inform the development and implementation of robust policy responses.

Improved flexibility in uncertainty and sensitivity analysis

The platform allows a scenario-based assessment of future cross-sectoral impacts and adaptation focussing on two timeslices (i.e., 2020s and 2050s) based on the four predefined socio-economic scenarios developed within the project (Figure 3.5). In addition, the high flexibility and uncertainty representation of the various individual (climatic and socio-economic) drivers in the IAP allows conducting an extensive sensitivity and uncertainty analysis by considering various scenario combinations of the driving forces that cover the full uncertainty space for longer time period (e.g., up to 2100). This is particularly important as the commonly used four-scenarios-based approach: (i) cannot fully represent the possible uncertainty space that takes into account the uncertainties of possible combinations of the individual drivers representing several plausible future scenario realizations, and (ii) can also introduce additional uncertainties originating from the very nature of the commonly used 2-dimensional scenario development processes and the associated limits to knowledge, personal judgement (including beliefs and axiomatic preconceptions), and the challenges and/or simplifications used in the quantification of scenarios with models. The need for a higher dimensional scenario development process has already been highlighted in recent studies. For example, Hallegatte *et al*. (2011) emphasised the challenge in identifying the most important dimensions that represent the directions over which world's societies and economies evolve over time. Consequently, they identified three key dimensions (considering the results of a combination of driving forces), which take into account the most relevant socio-economic factors that define the vulnerability of human systems to climate change and their ability to adapt to it. In addition, the recent scenario framework considered in the IPCC's fifth assessment report also highlighted the need for a new approach based on the concept of Shared Socio-economic Pathways (SSPs) (e.g., O'Neill *et al*. 2014). The new scenario development framework allows consideration of more than four scenarios that are consistent with the scenarios of future radiative forcings (known as the Representative Concentration Pathways, RCPs) (see van Vuuren *et al*. 2011). However, providing more flexibility in the choice of scenario combinations of various drivers, rather than using the limited (usually four) scenarios, in IAMs allows a better exploration of the space of uncertainty that can help identify robust measures across scenarios as well as sectors/sub-systems and regions.

Intuitive user interface design

The IAP's GIS-based user interface (which contains four different screens: *Impacts*, *Adaptation*, *Vulnerability*, and *Cost-effectiveness*; see Section 3.2) is "designed to facilitate a two-way iterative process of dialogue and exploration of various 'what if' questions" (Harrison *et al*. 2013, p.768). This is achieved through the development of an intuitive and user friendly interface that allows stakeholders to use the platform with minimal assistance and "recourse to help files and, importantly, without the need for training" (p.768). In this context, the CLIMSAVE IAP interface design improves on other participatory model interfaces and potential user requirements to provide: (1) simplified model set-up and run-times, (2) better understanding of the sectoral and cross-sectoral impacts and evaluate effects of adaptation in reducing the impacts, (3) simplified tool-tips for on-screen user guidance, (4) improved flexibility to conducting sensitivity analysis and exploring uncertainty of individual climatic and socio-economic drivers and associated scenario combinations, (5) ability to view and explore spatial distribution of impact/adaptation/vulnerability indicators/metrics and be able to export model outputs for further offline analysis (Harrison *et al*. 2013).

Web-based platform and free user accessibility

The web-based design of the IAP provides improved accessibility and interaction, which provides more practical and effective use of the tool by stakeholders, more than a software-based design requiring installation of the tool on user's PCs (Harrison *et al*. 2013). In addition, the web-based design of the IAP and its free online accessibility for users also facilitates increased visibility of the tool within the web, which allows reaching more target users/stakeholders to raise awareness and provide better understanding about the issues surrounding climate change and associated potential impacts and adaptation needs. As highlighted above, the additional advantage of the multi-models coupling integrated methodology used in the development of the IAP based on a meta-modelling approach also allowed leanest representation of sectoral processes for inclusion within the IAP. Consequently, the fast IAP simulation time associated with such meta-models allowed rapid iteration and identification of the most important driving factors and cross-sectoral impacts within seconds of run time. This was an important factor in the design of the tool as a web-based platform, as both functionality and speed of model runs are key aspects of such web-based tools in engaging users without getting bored (i.e., long model run-time discourage users from engaging with the platform).

7.4.2 Potential improvements

Despite the number of key features (strengths) outlined above, the CLIMSAVE IAP, as is the case with other similar complex integrated models, also have some limitations. These limitations need to be considered not only in future improvement of the CLIMSAVE platform itself but they could also be considered in informing the development of the next generation of IAMs in general. Following the sensitivity and uncertainty analysis, the following key limitations of the IAP as well as that of the individual sectoral meta-models integrated within the platform are identified and discussed here. In terms of the integrated framework of the IAP, the potential improvements that need to be taken into account in its future versions and where relevant in developing the next generation of IAMs include: (1) incorporating missing links and dynamic feedbacks between the sectors/sub-systems, (2) considering additional key sectors/sub-systems that are also important within the socio-ecological systems nexus, (3) refining selection of sectoral and cross-sectoral indicators/metrics, (4) maintaining similar level of complexity between the various sectoral models, (5) improving on the issues of scale (both spatial and temporal), (6) improving on flexibility of the integrated platform to allow running the individual sectoral models in both linked and unlinked mode, (7) adding capability for automated multiple integrated model runs in batch version on the web, (8) translating the IAP from exploratory tool to decision support tool, (9) updating the climate and socio-economic scenarios with the latest RCPs and SSPs, (10) considering dynamic implementation of adaptation taking into account changes in adaptation over time and associated feedbacks, and (11) developing a clear and easy-to-follow user’s guide. They are discussed below in more detail.

Incorporating missing links and dynamic feedbacks

The current CLIMSAVE IAP captures several key linkages and interactions between the various sectors/sub-systems integrated within the platform (as discussed in previous chapters, also see Figure 5.1). However, there are some important missing linkages/interactions between the sectors/sub-systems that could be considered in future IAP improvements. In addition, while focusing only on two snapshot timeslices, the CLIMSAVE IAP does not explicitly take into account the potential temporal dynamic feedbacks in terms of changes (within and between sectors/sub-systems) with time. Two key examples of missing linkages and feedbacks between sectors/sub-systems that are identified here are: (i) *Urban & flooding*: the link in terms of the effects of urban change drivers such as 'Coastal attractiveness' and 'Compact vs sprawled development' on flooding is currently missing as they both don't have any direct/indirect effect on the number of people flooded in the current modelling system. Similarly, the indirect effect of GDP on the number of people flooded through its effect on urban change is currently not captured. Furthermore, while the effect of urban growth on the number of people at risk of flooding is being modelled, the implication of future risk of flooding on urban planning is not captured sufficiently; and (ii) *Agriculture & forestry*: in line with the assumption on food prioritization in the current CLIMSAVE modelling system, the feedback from forestry on agricultural land use is not considered. Therefore, future development of the IAP need to consider revisiting the points of contacts between the various sectors/sub-systems in order to improve the platform by creating a dynamic version of the IAP that incorporates the missing important linkages and interactions and captures key temporal dynamic changes and associated feedbacks between the sectors/sub-systems. Some improvement related to these issues is being considered in a follow-up new project, IMPRESSIONS[24], which builds on the CLIMSAVE integrated modelling framework and focuses on advancing understanding of the potential implications of high-end climate change scenarios (with temperature increases more than 2^{o}C) in order to facilitate decision-making on integrated adaptation and mitigation strategies.

Adding other key sectors/sub-systems

The CLIMSAVE IAP is a landscape IAM focussing on six key land- and water-based sectors/sub-systems (Chapter 3). However, with the growing paradigm shift towards a 'nexus' approach in climate change adaptation, a comprehensive understanding of the socio-ecological systems nexus needs a more robust system-of-systems integration of the coupled human and natural

[24] Impacts and risks from high-end scenarios: Strategies for innovative solutions (www.impressions-project.eu).

systems. This requires improved representation of the various key components of resources and indicators of associated sustainability challenges. Such an understanding requires the development and quantification of holistic modelling frameworks and IA tools which, in addition to the sectors/sub-systems considered in CLIMSAVE, also takes into account other important socio-economic, environmental and resources sectors/sub-systems (such as human health, energy and other infrastructure systems (e.g., transport), fishery, tourism, etc.; see Table 2.1) integrated in a single overarching framework as comprehensively as possible. For example, it has been argued that framing climate change impacts and adaptation challenges as a public health issue (in addition to, rather than just, as an environmental issue, which lacks personal relevance to individuals and communities) provides a better platform for engaging the population with climate change (e.g., Weathers and Kendall 2015). Therefore, incorporating such sectors/sub-systems in future IAMs is crucial to provide a comprehensive understanding of the potential impacts and design improved alternative pathways for robust adaptation policy responses.

Refining selection of key indicators/metrics

In the current version of the CLIMSAVE IAP, a single model run generates a large amount of data (with a size of about 20MB CSV file per run). This data involves a total of about: (i) 110 input settings representing specific values of the various driver variables (i.e., climatic and socio-economic factors), and (ii) 170 IAP output variables representing various sectoral and ecosystem service indicators (including intermediate outputs of individual sectoral models). These variables define the overall model run time and computational power required for running the platform. However, focusing only on key sectoral and cross-sectoral impacts and adaptation indicators/metrics that are relevant to stakeholders and prior screening of parameters for minimizing the number of less relevant model outputs will provide greater opportunity for improving the individual sectoral models as well as the integrated platform in a number of ways. For example, it can provide the opportunity for either (i) adding more sectors/sub-systems instead of having a large number of model outputs of a same sector/sub-system with not all of them being relevant for stakeholders and/or (ii) reducing model run times and the associated computational power required. Therefore, future development of such models needs to consider a stakeholder-led prior selection of the key sectoral and cross-sectoral indicators/metrics of impacts of and vulnerability and adaptation to climate and socio-economic changes that are most relevant to stakeholders' needs and for adaptation policy making. This will require integrating stakeholders' inputs starting from defining the focus of the integrated models being developed to inform the selection of the key policy-relevant metrics. However, it is worth stating that with the emergence of 'Big Data' technologies, future use of IA tools could also benefit from related data storage, querying and mining techniques in order to extract important information from the ever growing complexity of such systems integration models, for example, in terms of identifying crucial patterns between inputs-versus-outputs (as in the case of the ODAT and MDAT analysis presented in Chapters 5 and 6, respectively) or outputs-versus-outputs (such as sector/sub-system versus sector/sub-system or spatial correlations) more comprehensively.

Maintaining similar level of complexity between sectoral models

Another key aspect of IAMs is the level of complexity of component/sub-models and their interactions within an IAM. Hence, integrating individual sub-/models with similar complexity is an important compromise, as this has important implications on balancing the optimum level of trade-offs between the overall detail and accuracy of IAMs (e.g., Schneider and Lane 2005). In the CLIMSAVE IAP, the land use meta-model is relatively more complex (with various interactions and feedbacks between sub-components) than the other sectoral models. Although on the positive side, the land use modelling system may be more realistic, it adds significant complexity to the overall integrated model, which may hinder easier understanding of the interactions between the various sectors/sub-systems integrated within the IAP. In addition, the land use model itself necessitates a comprehensive stand-alone sensitivity analysis for testing and validation purposes, which also adds to the challenge of performing a comprehensive sensitivity and uncertainty analysis of the integrated model as a whole. Therefore, it is worth noting that, while a comprehensive calibration and validation of multi-model coupled IA tools as a whole may still prove a challenge, maintaining similar level of complexity in terms of balancing the level of detail of the various sectoral models (as well as their individual components) plays an important role for systematically testing complex integrated models as a whole as sufficiently as possible (as demonstrated in this thesis) and for estimating and reducing their uncertainty (e.g., Dunford *et al*. 2014). One way forward is, for example, a consistent use of dimension reduction using emulation techniques across the various system models (Holden and Edwards 2010; Holden *et al*. 2014).

Improving on the issues of spatial and temporal scales

Scale is important when dealing with complexity in systems integrations. The CLIMSAVE IAP operates at a 10' x 10' grid resolution (for the European IAP) and 5km x 5km grid resolution (for the Scottish IAP) in the data exchange between the various sectoral models and the final aggregation of the integrated model outputs. These spatial resolutions were selected to match the available baseline climatologies for both Europe (which uses CRU's[25] data land grids; see Mitchell *et al*. 2004) and Scotland (which uses the UKCP09 climate scenarios with the selected spatial details). While the individual models operate at finer scales and use different data with finer resolutions (e.g., use of a 100m gridded CORINE land use data, hydrology simulation at river basin scales, etc.; see Section 3.2 for more details), the selected grid resolutions of the IAPs represent a compromise between the scale of available harmonized datasets, model run-time (and computational power and efficiency) and spatial detail of the integrated model outputs. However, improving on issues of balancing the compromise between the selected spatial data resolution and associated aggregated data transfer across sectoral models (e.g., for flooding) with the overall complexity of the integrated model will provide more robust results. In addition, the focus on the two timeslices (i.e., 2020s and 2050s) used within the current modelling approach could be improved by considering a dynamic time-series modelling approach (also extending the modelling framework to 2100). This can provide comprehensive projections of future impacts across different temporal scales (e.g., considering time series of a 10-years timestep) to inform the short- (e.g., 2020s), medium- (e.g., 2050s), and long-term (e.g., 2080s) risk management and adaptation planning in the face of uncertainty. Moreover, the use of percentage change in drivers from baseline in the current modelling approach in the IAP assumes unchanged spatial distribution of drivers with time. However, this does not capture the possible future changes (from the baseline) in the spatial pattern of the various drivers. In addition, adaptation measures in the IAP are also implemented as a single percentage change from the 'no adaptation' scenario. Hence, improving on handling of future changes in the spatial patterns of the drivers (both climate and socio-economic factors) relative to the baseline distributions as well as potential spatial adaptation measures relative to the 'no adaptation' option is crucial in order to provide better predictions of future impacts and vulnerabilities as well as implementation of adaptation measures.

Improving on flexibility of IAP for running models in linked and unlinked mode

While earlier (not publically available) version of the IAP allowed accessibility of individual meta-models for performance testing purposes during the developmental stages, this is now no longer the case in the current openly available IAP version. However, another important improvement in future IAP version is to consider additional flexibility of the platform and accessibility in terms of creating a version of the IAP which allows running the individual sectoral meta-models both as a linked (i.e., integrated version, including with the option of

[25] Climatic Research Unit: http://www.cru.uea.ac.uk/

selecting a set of models integration only or integration of all models) and as a stand-alone mode (i.e., unlinked version). This allows assessing sector/sub-system-specific responses of indicators as well as the potential effects of integrating cross-sectoral interactions on impacts and adaptation under future changes in the climatic and socio-economic drivers and scenario combinations. This will provide interested users and stakeholders with a better understanding of the interactions and a comparison of future impacts with and without the interactions between the various sectors/sub-systems. This is important to understand effects of the sectoral model integrations on both the magnitude as well as spatial distribution of future cross-sectoral impacts relative to those without the interactions).

Adding capability for automated multiple model runs in batch mode

The IAP being a freely available online-based tool is a key feature over other similar but PC software-based models as it increases accessibility and a wider use of the platform by interested citizens. However, the current web-based version of the IAP allows only one run at a time on the web. As a result, exploring the full flexibility and capability of the IAP on the web could be a very time-consuming task. Consequently, running the current version IAP in a batch mode for performing hundreds/thousands of model runs at a time (as in the case of the runs used in this research) is only possible offline, through the TIAMASG Foundation[26] (CLIMSAVE project partner based in Romania), where the server is currently being hosted. So, this could have implications (limiting factor) on wider use and application of the platform more generally, and continuation of its improvement in the long term. Hence, allowing a batch mode run on the web will be another important factor to consider in future improvement of the IAP. As such, it will provide the opportunity to explore the full capability of the IAP, e.g., in terms of performing extensive sensitivity and uncertainty analysis of future cross-sectoral impacts and adaptation needs under various scenarios. The ERMITAGE[27] portal is an example with such feature that can be considered in future improvements of the IAP as well as development of the next generation of IAMs for impacts and adaptation assessment.

Translating IAP from exploratory to decision support tool

Another important aspect of future IAP improvement is to consider translating the current IAP use/application from being an exploratory assessment tool to a decision support tool for increasing policy relevance and informing adaptation decision-making. Such improvements

[26] Foundation for Applied Information Technology in Environment, Agriculture and Global Change; Web link: http://www.tiamasg.org
[27] ERMITAGE: Enhancing robustness and model integration for the assessment of global environmental change (FP7 Project: http://ermitage.cs.man.ac.uk/).

could consider various approaches and directions, for example: (i) as most governance and adaptation policymaking take place at the regional/national scale rather than continental scale, future development of the integrated methodology as a decision support tool need to focus on such relevant scales and requires: (a) tailoring the IAP based on the particular/regional data and requirements and associated adaptation objectives, and/or (b) incorporating the IAP within available national/regional climate change adaptation platforms; and (ii) in order to facilitate adaptation decision-making through providing policy-relevant information on overall ranking of options, future improvement of the IAP could also consider combining the IAP with a specialized multi-criterial decision analysis (MCDA) tool components (e.g., the web-based MULINO Decision Support System, mDSS software; Fassio *et al*. 2005): (a) to use the various sectoral indicators/metrics of the IAP for exploring various adaptation decision options across sectors/sub-systems, and (b) to evaluate the benefits of adaptation decision options in the context of different regional and stakeholders perspectives, as discussed and being considered by the CLIMSAVE team.

Updating scenarios to the latest RCPs/SSPs

The CLIMSAVE IAP uses various climate and socio-economic scenarios integrated within the platform. The climate scenarios are based on outputs of five selected climate models from the IPCC AR4 (i.e., HadGEM, GFCM21, IPCM4, CSMK3 and MPEH5). On the other hand, the socio-economic scenarios integrated in the IAP are developed with stakeholders as part of the project through a series of professionally coordinated stakeholders' workshops (Section 3.4). However, future improvement of the CLIMSAVE IAP could consider updating both the climate and socio-economic scenarios with the recently developed scenarios used in the IPCC 5th Assessment Report by translating the Representative Concentration Pathways (RCPs) and Shared Socio-economic-pathways (SSPs) for both the continental (Europe) and regional (Scotland) contexts. The two sets of scenarios of the IPCC AR5 have been developed to provide robust scenarios with a point of commonality across the research communities. Such common scenarios allow a consistent analysis both through the use of the scenarios in IAMs as well as in detailed sector/sub-system-specific modelling frameworks, which makes it possible for comparing and integrating various detailed studies across sectors/sub-systems and regions.

Considering dynamic adaptation and feedbacks

In the current CLIMSAVE IAP, adaptation is implemented as a percentage change from the baseline condition for the two snap-shot timeslices (i.e., the 2020s and 2050s), which is often partly/fully independent from the scenarios. In addition, it does not take into account both the spatial and temporal dynamics of and feedbacks between different adaptation strategies that are integrated within the platform. These issues have important implications on informing, for example, the local and national adaptation decision-making. Therefore, future improvement of the IAP needs to consider the spatial representativeness of the temporal dynamics and feedbacks in implementation of adaptation options taking into account time-, scenario-, capital- and spatial scale-dependency in order to increase policy-relevance of the IAP as well as in informing development of the next generation of IAMs.

Developing a clear and easy-to-follow users' guide

Finally, since the use and understanding of such complex integrated models raise important challenges to stakeholders and interested users who were not part of the team that developed the tools, developing a clear, detailed and easy-to-follow user's guideline of the tool and the key interactions/linkages and feedbacks considered could be crucial. It will provide a useful guidance to unfamiliar users for a better use of the tool and to avoid misinterpretation and unrealistic use and expectation of model results.

In addition, the key current limitations and potential future improvements for the individual sectoral meta-models are discussed as below. The issues or potential improvements identified here could also initiate discussion between sectoral modellers to inform development of future generation of sectoral models for incorporating them in IAMs.

Urban: The RUG meta-model

The urban model uses a meta-modelling approach based on grid-based look-up data tables, where pre-processed data tables representing the various scenario model runs are read using a simple look-up algorithm to calculate relative changes in artificial surfaces compared to the baseline distributions. Such approaches are inherently subjected to step-change approximation of projections based on nearest scenarios that are included within the pre-processed look-up data tables. Future improvement of the IAP needs to consider either interpolation of projections between the pre-defined scenarios or using other continuous urban growth prediction modelling approaches such as ANNs (e.g., Triantakonstantis and Mountrakis 2012). In addition, the current urban change modelling system uses 'growth-only' assumption, and it doesn't simulate potential shrinkage in artificial surfaces. Although, this is mostly the case and it applies for most European cities in terms of changes in urban land areas (Haase *et al*. 2013a), such an assumption may also have important implications when predicting the distribution of population for some urban areas. This is especially important when studying the phenomenon at a continental or larger area scales where there are some cities with shrinking population, as this also has important implications on other sectors/sub-systems, such as predicting future flood impacts on people. For example, Haase *et al*. (2013b) reported that more than 40% of all large European cities particularly in eastern Europe are currently shrinking with a considerable and continuous decline in population. Hence, future improvement of the model needs to take into account the phenomena to realistically represent the current distribution and predict future population distribution and concentration hotspots across cities, including areas with declining population due to various factors, such as demographic, social, physical, economic, and environmental trends.

Flooding: The CFFlood meta-model

Similarly, some key limitations and/or potential future improvements for the flood model (which includes three sub-models: coastal flood, fluvial flooding, and habitat change/loss models) are also identified. Firstly, one aspect of the flood model is the use of a step-change based representation of the topographic data with a 25cm interval elevation band pre-processed look-up data tables. Currently, modelling of the area of land at risk of coastal flooding assumes the bathtub approach based on nearest-elevation band for estimating areas of flood prone zones under the extreme water levels projected between the 25cm interval elevation bands. This has important implication on the balance between model run time and accuracy (i.e., precision of the coastal flood module), and it is particularly important as the effect of sea-level rise (with similar order of magnitude) is also sensitive to the assumption. Therefore, future improvement of the flood model needs to consider either a continuous interpolation between the bands or other inundation modelling approaches that better represent floodplain topography and associated (spatial as well as temporal) dynamics of inundation. Secondly, under the current fluvial flood modelling approach, there is no distinction between the impacts of precipitation due to the seasonal variations, as impacts are sensitive only to the magnitudes of change in precipitation regardless of the seasonal changes. Future improvement need to take into account the temporal dynamics of impacts due to the seasonal variations. In addition, future improvement could also consider policy-relevant impact indicators (e.g., Expected average annual estimates instead of flood event-based estimates of impacts) and other types of flooding (such as surface water flows, drainage flows, etc.).

Agriculture: The SFARMOD and CropYield meta-models

One of the most important assumptions to recognise in the SFARMOD model and hence the CLIMSAVE IAP is that the rural land use allocation module has an implicit in-built autonomous adaptation. The model prioritises food production in the rural land use allocation process, and if it is not possible to meet European food demand with the existing land use distribution, the module autonomously expands agricultural land to meet demand. This means that any driver that has an impact on food demand or agricultural production has a considerable indirect impact on all other sectors/sub-systems that are dependent on land use, such as forestry, biodiversity and landscape diversity. The model also makes scenarios where food provision is de-prioritised, for example to focus on forest products (such as timber production) or biodiversity, but this is often harder to replicate within the platform. Therefore, further extensions of the project in improving the IAP could re-consider the prioritisation within the land use model. For example, Edwards *et al*. (2013) highlighted that balancing increased agriculture intensification (e.g., for supporting biofuels while meeting food demand) with maintaining terrestrial carbon storage in forest ecosystems can be achieved in an economically efficient way under strong mitigation scenarios. However, with a better understanding of the IAP, the current integrated modelling system as a whole still has considerable value in terms of highlighting the importance of dealing with food security issues in Europe. Firstly, it is important to note that although food production is prioritised in the land use model, with an understanding of the system, it is still possible to compensate for the priority given to food within the existing system. One way to do this is to decrease the proportion of demand for food that is not expected to be provided by Europe's agricultural land area through increasing, for example, 'food imports'. Secondly, the system does highlight the importance of food security as a key issue driving the future of European landscape change dynamics and the importance of land use in decision-making: including the considerable knock-on effects on all other sectors/sub-systems (Kebede *et al*. 2013).

Forestry: The metaGOTILWA+ model

The forestry model focusses on five tree species considered in the CLIMSAVE IAP, which are: *(1) Pinus sylvestris, (2) Pinus halepensis, (3) Pinus pinaster, (4) Quercus ilex, and (5) Fagus sylvatica*. While these tree species represent the main types of trees in Europe, three potential improvements identified include that: (i) the current modelling system does not allow changing from one tree species to another under scenarios with expanding forests (i.e., if a grid cell has a certain type of tree, future expansion of forest areas considers only expansion of the same tree than other species of the five tree species considered), (ii) the model does not consider the potential of planting new trees if there was none in a cell at the baseline, and (iii) considering adding other tree species than the five included. Therefore, potential future model improvement could consider taking into account these in order to provide a comprehensive picture of the impacts on forests under changing future conditions for devising appropriate adaptation responses. In addition, it is worth noting that as highlighted above in the rural land use allocation model, the prioritization for food production has important implications for estimates of the total timber production under future scenarios, as presented in this study. This also needs to be considered in future improvement of the forest model to take into account the dynamic feedbacks with agricultural land use and associated indirect effects of future socio-economic changes in addition to climatic factors.

Water: The WaterGAP meta-model

The water meta-model incorporated in the CLIMSAVE IAP is based on the more detailed and advanced global hydrology and water use model, WaterGAP (Water – Global Assessment and Prognosis; see Wimmer *et al*. 2015). In so doing, the meta-model considers key assumptions for simplifying the original model in order to satisfy the key requirement of the IAP in terms of balancing the compromise between model run time and accuracy. The three main assumptions that could be considered in potential future improvement of the water meta-model are highlighted here (Holman and Harrision 2012). First, it is related to the issue of scale in terms of dis-aggregating estimates of the changes in river discharge at the river basin scale to the CLIMSAVE 10’ x 10’ grids downscaling approach assumes a uniform relative change in discharge across all grids within a river basin network – although a river routing in reality is a non-linear process and this can have important implications especially for those large basins. Second, currently the water use in agricultural sector/sub-system is not explicitly covered in the water meta-model as in the case with the other three sectors/sub-systems considered (i.e., domestic use, manufacturing industry, and thermal electricity production), it is rather informed by the land use model, which considers the available water for agricultural use estimated by the water model as the ‘maximum allowed water withdrawals for irrigation’. The water model uses an iterative prediction of total water consumption (including agricultural use) based on a ‘water sharing rule’ applied uniformly across all sectors/sub-systems assuming ‘baseline proportions’. Although, the IAP allows users to choose various water-sharing rules, such an assumption does not take into account future prioritization of sectors/sub-systems that could have significant implications for the water balance through changing total consumptions of water across the various sectors/sub-systems. Therefore, future improvements need to consider: an explicit account of the agricultural sector/sub-system water use within the water model with consistent assumptions across the sectors/sub-systems and/or improved linkages between the land use model and water models to capture the feedback between them for a more realistic prediction of the water balance under future changing socio-economic and climatic conditions. Third, the model uses dis-aggregated monthly precipitation input data to simulate daily river discharges that are used to derive key output parameters (i.e., Q_{med}, Q_{95} and Q_5, which also have implications for other sectors/sub-systems such as flooding, biodiversity, and agriculture) estimates, and future model improvements could consider using or integrating (available) daily precipitation time series observation data for improved predictions. Fourth, while the water meta-model feeds the SPECIES model in terms of the available environmental flows under a given scenario, potential feedbacks from the biodiversity model to the water model in terms of informing future minimum environmental requirements are currently missing, and need to be taken into account in future improvements.

Biodiversity: The SPECIES meta-models

A key factor to highlight is that, in order to allow users to be able to run the IAP on the web with short (few seconds) model run time, the biodiversity indicator (i.e., biodiversity vulnerability index) considered in this study uses a selected representative list of 12 species (out of the total 111 available species incorporated in the Platform). The biodiversity indicator included in this study (focussing on the 12 representative species) was used to highlight the combined effects of both changes in land use (indirect impacts due to both climatic and socio-economic factors) as well as the (direct and indirect) impacts due to changes in the climatic factors on availability of appropriate habitat and climate space for biodiversity. The 12 selected species are: *(1) Common poppy (Papaver rhoeas), (2) Linnet (Carduelis cannabina), (3) Bilberry (Vaccinium myrtillus), (4) Hornbeam (Carpinus betulus), (5) Norway spruce (Picea abies), (6) Brown bear (Ursus arctos arctos), (7) Western dappled white butterfly (Euchloe crameri), (8) Common saltmarsh grass (Puccinellia maritima), (9) Strawberry clover (Trifolium fragiferum), (10) Bell heather (Erica cinerea), (11) Red deer (Cervus elaphas), and (12) Capercaillie (Tetrao urogallus)*. Hence, the behaviours observed and presented in this study are inherently limited to those species within the selected set of species considered in this analysis. The indirect implications for other types of species (e.g., that are not included in this analysis) could lead to sensitivity trends that are different from those presented here. In addition, with the aforementioned priority given to food production having a knock-on effect on biodiversity vulnerability index, the results presented here mainly reflect the indirect effects of the drivers on the spread of arable agriculture related species, which might for example over-represent the importance of arable habitat in contrast to other species. However, it is worth noting that the study also reflects the potential indirect implications of future changes on arable-related species, as almost 50% of species in Europe depend on arable habitats (EEA 2005). Nonetheless, future improvement of the IAP need to consider improved versions of the biodiversity model with broadening of the selected representative species group in order to take into account the overall vulnerability of the diverse species included in the tool, although the 111 species incorporated in the platform were selected to focus on species which interact with the other sector/sub-systems s considered in CLIMSAVE. Therefore, future improvement could also consider incorporating other species that are currently under-represented within the selected representative groups that have important cross-sectoral implications.

7.5 Future Directions for the Next Generation of IAMs at Sub-global Scales

An important challenge in understanding and responding to the issues of climate change is that impacts are often a result of several (competing and/or complementing) interactions, feedbacks, and trade-offs between the different socio-economic activities and environmental processes and associated impacts and uncertainties (Skaggs *et al*. 2012). Consequently, modelling and understanding the interactions and feedbacks between various socio-ecological systems requires not only accurate representations of each individual sectors/sub-systems and their components, but also a detailed understanding of the scale-dependent interactions within and between the various sectors/sub-systems. Addressing global climate change and sustainability related questions that decision makers at various scales are asking will require the development and application of systems integration models capable of: (i) assessing the potential future climate and socio-economic change impacts, (ii) evaluating different adaptation strategies, (iii) testing different mitigation options, and (iv) accounting for interdependencies and potential trade-offs, co-benefits, and uncertainties associated with these policies or combinations of various policy responses (see Figure 2.1). Even though there has been significant progress in systems integration and integrated assessment of climate change, many important challenges still remain in terms of the role of IAMs in informing and supporting scale-relevant adaptation polices and decision-making (Liu *et al*. 2015; Verburg *et al*. 2015). For example, integrated frameworks have been developed and applied largely in isolation for individual sectors/sub-systems, although they are interconnected through human activities and environmental processes (e.g., using more ecosystem services may lead to larger environmental footprints). "Achieving a greater degree of integration would involve analysing and managing coupled human and natural systems over longer time periods, larger spatial extents (for example, macrosystems and ultimately the entire planet), and across more diverse organizations at different levels" (Liu *et al*. 2015, p.6).

In this regard, in addition to the various issues discussed in previous sections, a number of key future directions are identified and described below. These factors need to be considered to systematically and comprehensively advance systems integration and modelling approaches in order to enhance the relevance of IAMs in informing climate change adaptation and mitigation policies and resources management decision making processes at appropriate scales:

(1) Integrating more socio-ecological sectors/sub-systems simultaneously and more comprehensively,
(2) Identifying and focusing on the most important components and their interactions within each sector/sub-system integrated,
(3) Identifying and quantifying both direct and indirect linkages (point of contact) and interactions between systems,
(4) Identifying and explicitly taking account of feedbacks between systems,
(5) Integrating multiple spatial and temporal scales and organisational levels,
(6) Considering both climatic and socio-economic change drivers holistically,
(7) Incorporating adaptation and mitigation policies explicitly and dynamically,
(8) Explicit treatment of uncertainty,
(9) Improving on existing integrated frameworks and developing and applying new tools, and
(10) Designing IAMs as decision-support tools for translating findings into policy and practice.

Integrating more sectoral systems simultaneously and comprehensively

Although some previous studies have considered multiple components of the coupled human and natural systems, many components still are either not considered or treated as external factors/drivers rather than being holistically integrated (Liu *et al*. 2015). Such partial treatment of socio-ecological systems with a focus on parts of the system components in at a particular scale will not capture all important interactions and feedbacks between the key components. This can lead to incomplete picture of the socio-economic and environmental systems interdependencies and associated inconsistencies and even incorrect conclusions regarding our understanding of the interconnections and functioning of the various systems. This will have significant implications for devising appropriate response measures and sustainable solutions to deal with the trade-offs between various systems. Therefore, development of future IAMs needs to consider integrating more sectors/sub-systems and incorporating all important relevant variables holistically, so that their dynamics and feedback effects are explicitly studied (Liu *et al*. 2015). Combining different complex systems integration approaches in various disciplines such as those with complex adaptive systems (e.g., Levin and Lubchenco 2008) can provide innovative ways to integrate disparate ideas and various systems components in order to understand temporal dynamics and sustainability of the coupled human and natural systems.

Identifying and quantifying both direct and indirect systems' linkages and interactions

Sectoral studies focus on sector/sub-system-specific issues, with detailed consideration of the various components of the sector/sub-system without taking account of the potential effects to and from other sectors/sub-systems. However, most integrated assessment studies often focus on direct interactions between the systems considered, with little attention to not only the indirect interactions but also to indirect effects in terms of either other systems (that affect and/or are affected by the interactions between sending and receiving systems) or regions, which may also have feedbacks that may affect sustainability of the systems considered within and across scales. Even though there are some previous studies which to some extent recognize indirect effects on external systems (e.g., Andam *et al*. 2008) or spatial externalities such as urban-rural land use interactions (e.g., Pacheco and Tyrrell 2002;), they are often focussed on either socio-economic or environmental aspects or specific scales, rather than considering all effects simultaneously and at appropriate scales (Liu *et al*. 2015). Moreover, other components of these systems such as causes, agents, and flows and interconnections between distant places (as demonstrated by Liu *et al*. 2013 in a coupled framing of global sustainability) are rarely considered. Therefore, tailoring IAMs for identifying and quantifying all important components of the socio-economic and environmental systems including indirect systems and spatial externalities can help better understand the complex interactions between systems (Liu *et al*. 2015). As such, this will allow a critical appraisal of the dynamic interrelationships among different systems and scales in order to develop more effective management strategies and adaptation and mitigation policies.

Identifying and explicitly taking account of feedbacks between sectors/sub-systems

Feedbacks between various human activities and environmental processes are an important component of coupled systems processes and sustainability. However, while they may have significant implications for understanding the systems interactions, many integrated assessments often do not take into account feedbacks (feedback mechanisms) and associated trade-offs and synergies across multiple systems (Liu *et al*. 2013). A framework of telecoupling has been identified as an innovative approach in order to identify and use feedbacks as important mechanisms for sustainability (Liu *et al*. 2013; 2015). Hence, future systems integration studies could consider integrating such approaches/frameworks in order to explicitly consider feedbacks between the various socio-ecological systems for devising appropriate sustainability solutions.

Integrating multiple spatial and temporal scales and organisational levels

Human and natural systems and associated processes and patterns at multiple scales show characteristic variability, and they also interact with each other over a range of spatial and temporal scales and across different organisational levels (Wilbanks 2002). Therefore, multi-scale and multi-level approaches are required in integrated analysis and modelling approaches for dealing with systems interactions. For example, while food production at the local or regional scales is mainly driven by socio-economic factors at the respective scales, the long-term sustainability planning of food security issues would also require taking account of its environmental implications (e.g., GHG emission) at the global scale. Hence, considering systems interactions at multiple spatial scales at the same time can help identify all the important and relevant factors, their interdependence, and their effects and nonlinear relationships within and across the systems and scales. Similarly, in terms of temporal scales, combining short-term studies with long-term studies helps in maximising the strengths of each assessment approach at the different scales in order to better understand the temporal dynamics of systems interactions and feedbacks (Liu *et al*. 2015). For example, while studies focussing on short-term systems changes may capture more subtle immediate system behaviour changes, studies on long-term system changes "may account for temporal dynamics, time lags, cumulative effects, legacy effects, and other phenomena (such as extreme events) that cannot be seen over shorter terms" (Liu *et al*. 2015, p.7). Therefore, more systematic incorporation of human dimensions (e.g., perceptions and associated behavioural responses) (e.g., Brondizio and Moran 2008) to long-term physical dimensions of systems changes plays an important role in understanding decision support needs for devising appropriate responses. In this regard, Wilbanks (2002) identified five key directions for improving capabilities in addressing the issues of scale and scaling in integrated assessments: (i) increasing the availability of local and small-regional scale data related to key issues and indicators, as this is an essential building block for indicator-driven modelling approaches, (ii) improving longitudinal database related to complex nature-society interactions and multiple stresses to increase our knowledge base regarding the interconnected phenomena and processes between nature and society, (iii) identifying key macroscale-microscale interaction issues and improve understanding of those key interactions in order to strengthen both the theoretical and empirical understandings of the major components of cross-scale dynamics, (iv) exploring tools for dynamic modelling of complex systems that are not widely used in IA modelling such as fuzzy logic, and (v) improving understandings of how to link analysis, assessment, deliberations, and stakeholder interactions for relating quantitative and non-quantitative contributions as appropriate and necessary as possible.

Considering climate and socio-economic change drivers holistically

As highlighted in previous sections, most climate change impact studies have typically focussed on the consequences (often sector/sub-system-specific impacts) of an assumed change in climate parameters (e.g., +2°C temperature change), without explicitly considering the effects of socio-economic factors. However, the use of IAMs in the analysis of climate response strategies considers the development and application of socio-economic scenarios, with a particular focus on climate change mitigation for achieving climate stabilization targets. With the recent advancement in the climate change and socio-economic change projections and availability of the RCPs and SSPs scenarios, future versions of existing integrated models or new developments need to consider both the climate and socio-economic change scenarios holistically. This will allow a better assessment of potential future impacts and adaptation as well as mitigation policy responses. Furthermore, Kriegler *et al*. (2014) have also argued that these scenarios augmented by shared climate policy assumptions to allow a comprehensive exploration of the scenario space, which can provide policy relevant information on adaptation and mitigation policies decision-making.

Explicit treatment of uncertainty

An important aspect of understanding and dealing with the challenges of climate change adaptation and mitigation is the need for incorporating and explicit treatment of uncertainty in integrated modelling frameworks and decision support systems (Letcher *et al*. 2013). Systems integration plays an important role in informing complex management and decision-making processes under uncertainty, as they are used as a key tool in the problem formulation for devising appropriate response measures in terms of evaluating management options and decision alternatives (Ravalico *et al*. 2010). As such, uncertainty remains an important factor that needs to be taken into account when developing any model, and it is particularly significant and often challenging when dealing with complex systems models (Kelly *et al*. 2013). Uncertainty in systems integration models may be due to various factors including uncertainties: (1) in system understanding (i.e., what processes should be included, how different processes interact), (2) in interpretation of data in relationship to the variables of interest (e.g., Linden and Mäntyniemi 2011), (3) in measurements used to parameterise the models, (4) in the inputs or conditions used for model runs, (5) related to issues of complexity in terms of ambiguities: (i) in the different perceptions of system definition and alternative causal structures (e.g., Mäntyniemi *et al*. 2013) or (ii) in the conceptualisation and problem framing due to multiple knowledge frame uncertainties (e.g., Brugnach *et al*. 2011; Henriksen *et al*. 2012). Hence, future improvements and/or development of systems integration and IA tools need to take into account these uncertainties explicitly. However, it is worth noting that for such complex dynamic models that aim at providing an integrated representation of the systems-of-systems interactions, validating their predictive accuracy is generally not straightforward due to a lack of appropriate data, especially for future predictions. This, on the other hand, highlights the issue of balancing accuracy of models (for providing sound policy relevant outputs) and their complexity (in terms of facilitating their wider use by stakeholders).

Improving on existing integrated frameworks and developing and applying new tools

Focussing on the key challenges of complex systems and integrated modelling approaches, more effective and comprehensive systems integration requires (Liu *et al*. 2015): (i) improving on current integrated modelling approaches based on refining and combining various existing frameworks and tools (e.g., merging short-term and long-term assessment approaches as appropriate) and (ii) developing and using new tools. Such future improvements of integrated analysis and modelling tools need to consider the challenges of: (i) overcoming difficult barriers (such as mathematical and computational challenges, quantification of impacts at one scale on other scales, and relationships among patterns and processes across systems-of-systems and spatial-temporal scales), and (iii) dealing with emergent challenges in terms of predicting unexpected 'surprises' and unforeseen threats for sustainability policy and management of resources (Liu *et al*. 2015). For example, agent-based models (ABMs) are becoming particularly promising tools as they integrate important interactions (e.g., human adaptation to environmental changes) at different scales and model the coupled human and natural systems as complex adaptive systems (e.g., An 2012). Unlike dynamic stochastic general equilibrium models (that presume a perfect world and ignore disturbances or crises) or the traditional empirical statistical models (e.g., econometric models; that are fitted to past data and fail when the future differs from the past), ABM approaches consider virtual worlds to simulate the real world (e.g., Farmer and Foley 2009). While a number of ABMs have been developed and applied in various studies and disciplines in order to provide insights on complexities and relevant information for policymaking in issues such as economic development and management of common spaces, some challenges still remain in terms of the wider application of these modelling approaches across scales. Hence, future improvements and development of new models need to consider these factors in order to account for tele-coupled systems across scales (Liu *et al*. 2013; 2015). Furthermore, with increasing computational power, existing ABMs can be improved or new ABMs can be developed by including more and more agents representing the various systems-of-systems components in larger areas and ultimately all important agents across the world. Also, with the emergence of various 'Big Data' mining techniques and more high-resolution data becoming available, future development of complex systems models can also benefit from various 'Big Data' tools (e.g., distributed databases, parallel processing, and cloud computing) for effective and efficient systems-of-systems integration and analysis across scales (Agrawal *et al*. 2015).

Designing integrated assessment models as decision support tools

With the exception of those that focus on informing mitigation policies, most IAMs still remain as exploratory tools. Moreover, various institutions and regulations have traditionally focused on single issues and often do not have the mandate or infrastructure to address the organizational connections and detrimental spill-overs across systems and scales (see Liu *et al*. 2015). Therefore, future directions in systems integration studies require both translating existing integrated models (which focus on 'what-if' questions) into and developing new decision support systems (e.g., multi-objective optimisation and multi-criteria analysis tools) for informing the policymaking process and supporting development of the necessary infrastructure and institutional capacity for a coordinated implementation of policies. Liu *et al*. (2015) highlighted that systems integration frameworks and methods tailored as decision support tools can provide more unbiased information for policy and practice in order to help clarify responsibilities (such as assigning responsibilities of addressing spill-over effects, e.g., CO_2 emissions reduction), mediate trade-offs, reduce conflicts, and anticipate future trends. Consequently, policy-relevant outputs of such multi-sector/sub-system and multi-scale integrated studies help improve coordination among multiple national and international policies, inform robust response strategies, and minimize trade-offs and conflicts between different policies (i.e., by avoiding conflicting goals and counterproductive implementation), as well as accelerating a better understanding of risk of global environmental change and solving challenges of global sustainability.

8. SUMMARY, CONCLUSIONS AND RECOMMENDATIONS

8.1 Introduction

With the growing focus in nexus-based (e.g., agriculture-water nexus, agriculture-biodiversity, food-water-energy nexus, etc.) climate change adaptation studies, more and more complex IAMs are being developed for assessing future impacts across multiple sectors/sub-systems and larger area scales. However, such models are very rarely examined comprehensively due to a number of factors, such as high complexity, lack of computational and human resources, unacceptably/prohibitively long model run time, etc. This consequently often limits a wider and continued use of these models by stakeholders (e.g., decision-makers) to whom they are intended) and their relevance in informing climate risk assessments and adaptation policy decisions. Moreover, despite the rapidly growing availability of increased computational power and better data, a comprehensive sensitivity analysis of such models by researches who are not the model developers is still rare. As such, these issues also contribute to the challenge on the extensive validation of such complex integrated models. This research is mainly driven by the need for such critical analysis and systematic application of a continental and large area scale IAMs.

The research aimed to address this gap based on a critical appraisal of IAMs through a systematic review of existing integrated approaches/frameworks and extensive application and examination of one European IAM, the CLIMSAVE IA platform (IAP). This allowed identifying potential areas of attention and future direction for uncertainty reduction to inform future improvement of the CLIMSAVE IAP as well as development of the next generation of IAMs. Based on an extensive application of the IAP, the research also aimed to: (i) provide new quantitative insights into the complex interactions of the European food-water-land-ecosystems (FWLE) nexus and associated synergies, conflicts and trade-offs; (ii) identify key sensitivities and overall uncertainties of the potential cross-sectoral impacts and adaptation policies under various scenarios of future changes in climate as well as social, economic, technological, environmental, and policy governance scenario settings in Europe; and (iii) develop a new nexus-based conceptual framework for informing long-term and multi-/cross-sectoral assessment and planning of robust adaptation policies. This was achieved by a combined approach drawing on a systematic: (i) Sensitivity analysis based on a One-Driver-At-a-Time (ODAT) approach, (ii) Scenario and uncertainty analysis based on Multiple-Drivers-At-a-Time (MDAT) approach, and (iii) Robustness assessment of adaptation policies (RAAP), across various sectors/sub-systems, scales and scenarios under a range of uncertainties.

The following sub-/sections present the key conclusions of the thesis and the recommendations for future research directions, outlined as follows. Section 8.2 discusses: (i) the role of IAMs for understanding the complex interactions of Europe's FWLE nexus and informing future cross-sectoral adaptation policies (Section 8.2.1), and achievements of the thesis in terms of the key outputs of the three objectives detailed in Section 1.3: (ii) The ODAT-based sensitivity analysis (Section 8.2.2), (iii) The MDAT-based scenario and uncertainty analysis (Section 8.2.3), (iv) The robustness assessment of adaptation policies (RAAP) (Section 8.2.4), as well as (v) the new nexus-based conceptual framework (Section 8.2.5), and (vi) limitations of the study (Section 8.2.6). Section 8.3 then summarises the overall key conclusions and recommendations for further research that have been highlighted in the process of this thesis, in terms of: (i) improving the CLIMSAVE integrated methodology and assessment platform (Section 8.3.1), and (ii) identifying potential areas of attention for uncertainty reduction and key future directions in informing development of the next generation of IAMs (Section 8.3.2). Finally, Section 8.4 presents key concluding summaries.

8.2 Achievement of the Research Aims and Objectives

The overall aim of the thesis was to provide a better understanding of: (i) the complex FWLE nexus interactions and associated synergies, conflicts, and trade-offs, and (ii) the key sensitivities and uncertainties of the potential cross-sectoral impacts of and adaptation policies under future climate and socio-economic change uncertainties in Europe. The study presented a systematic methodological framework that was developed and applied to investigate the direct and indirect implications of a wide range of climatic and socio-economic drivers and scenario combinations taking into account important cross-sectoral linkages and interactions between six key European land- and water-based sectors/sub-systems (*agriculture*, *biodiversity*, *coasts*, *forests*, *urban*, and *water*). The study focussed on seven key sectoral indicators (one per sector/sub-system plus one representing landscape multifunctionality): (1) Artificial surfaces (AS), (2) People flooded in a 1 in 100 year (coastal and fluvial) flood event (PF100), (3) Food production (FP), (4) Timber production (TP), (5) Water exploitation index (WEI), (6) Biodiversity vulnerability index (BVI), (7) Land use diversity (LUD). The key stages of the methodological framework by which the research aim was realised together with a summary of the key results and conclusions are presented below.

8.2.1 The role of IAMs in long-term adaptation planning under uncertainty

Integrated assessment approaches and models have been applied widely in order to investigate complex socio-economic and environmental processes and their interactions

(Letcher *et al*. 2013). However, the study highlighted that despite the rapid growth in the development and use of various systems integration approaches/models across a range of disciplines, scales and complexities, a particular focus has been on economy-wide integrated models for informing climate change mitigation policies. Those supporting integrated assessments of climate change impacts and adaptation across multiple sectors/sub-systems and scales are still relatively limited. In addition, a review of the literature showed that of those available landscape change IAMs, most still remain as exploratory tools to explore 'what-if' scenarios, often focussing on climate change drivers based on limited (usually four) scenario futures. This often limits their relevance in informing the decision-making process and long-term planning of robust adaptation policies. Consequently, the challenge in translating such models from exploratory tools to decision support systems still remains. Furthermore, while such tools provide valuable insights on the broad sensitivities of potential impacts to various future scenarios and different policy options, they do not allow assessment of more detailed response strategies that could inform the decision-making on the design and implementation of effective environmental policies and adaptation strategies. These challenges highlight the need for a continued effort on improving IAMs focussing on the key aspects of reducing such potential uncertainties for supporting cross-sectoral adaptation as well as mitigation policy decisions. Based on a comprehensive review of the literature, this research has identified ten factors as important criteria for: (i) selecting existing IA approaches and models, and/or (ii) providing guidance for developing future system dynamics models that are relevant for informing future adaptation policies and to improve effectiveness of decision-making and environmental risk management processes under deep uncertainty:

(1) The sectors/sub-systems (e.g., land, water, energy, ecosystems, etc.) and their components (e.g., sectoral metrics/indicators reflecting important biophysical, social-economic, environmental processes and their relevance to stakeholders and adaptation) identified as key components representing the coupled human-nature systems at a given scale,

(2) The choice of integrated modelling approaches (e.g., multi-models coupling, SD, BN, ABM etc.),

(3) The type and nature of integration (e.g., multiple sectors/sub-systems, issues, disciplines, stakeholders, scales, etc. and soft vs hard-linking),

(4) Treatment of climate and socio-economic drivers (i.e., specific focus on one or independent/holistic treatment of both),

(5) Treatment of adaptation (e.g., taking into account implicitly or explicitly) (as well as integrating with mitigation?),
(6) The level of spatiotemporal detail (e.g., scale (and up/down scaling) issues across sectors/sub-systems) and data availability/requirement (e.g., consistency of data used across models),
(7) Computational considerations and model run-time (e.g., level of complexity and issues of model validation),
(8) Treatment of uncertainty and capability for supporting sensitivity and scenario analysis, and
(9) The nature/type of the integrated platform/model (i.e., web-based or PC-based) and accessibility by end users (e.g., free or commercial),
(10) The level of assistance (and training) required to use the tools (e.g., is it user-friendly for stakeholders and policy-makers and encourage wider use and application?) and its relevance in supporting adaptation decision support.

Focussing on a continental and large area scale models, a review of the literature identified a number of existing IAMs which take into account these issues, at least partly (Section 2.4.3). However, the study highlighted that practical applications of most of these IAMs in supporting and informing decision-making on adaptation policies are often hampered due to a number of factors, e.g., their complexity, high mathematical and computational power requirement, long model run-time, limited nature of integration of key sectors/sub-systems as well as knowledge between stakeholders and scientists. These also limit their capability in supporting comprehensive sensitivity and uncertainty analysis, and their potential use and wider applications by various stakeholders and policy makers, and hence their relevance for decision support. A recently developed European integrated methodology, the CLIMSAVE IAP, addresses most of these issues through its holistic methodology framework by improving on existing tools in five important ways: (1) greater consideration of important cross-sectoral linkages and interactions between six key sectors/sub-systems (agriculture, biodiversity, coasts, forestry, urban and water), (2) holistic treatment of climatic and non-climatic drivers and high flexibility for supporting a comprehensive uncertainty and sensitivity analysis, (3) multi-scale application (European and Scottish), (4) greater integration of knowledge from stakeholders and scientists, and (5) its user-friendly and interactive exploratory 'web-based' tool with reasonably fast run-time and free availability for end users. While there are some limitations/potential improvement (as detailed in Section 7.4), the CLIMSAVE integrated methodology also demonstrated the key advantages of multi-models coupling approach as an important way forward. This is mainly because it provides vital flexibility (i) for combining various modelling approaches and in refining and validating individual sectoral/sub-system models/components, and (ii) to be able to replace/upgrade individual models as new methods, information or datasets become available in the future. The benefits of multi-models coupling approach have also been demonstrated in ERMITAGE by integrating complex models of climate change, economic, and energy systems (Edwards *et al*. 2013).

Furthermore, while there is some progress, a comprehensive sensitivity and uncertainty analysis of such complex IAMs is still very limited (e.g., Kriegler *et al*. 2014), and as such identifying the critical sensitivity drivers and associated uncertainty of future cross-sectoral impacts for informing integrated and multi-/cross-sectoral adaptation planning across scales still remains a challenge. Based on an extensive application of the CLIMSAVE IAP, this research assessed the complex interactions of Europe's FWLE nexus and identified the key sensitivities and uncertainties of future cross-sectoral impacts and robustness of adaptation policies under various future scenarios of climate and socio-economic change and associated uncertainties. This was achieved using a systematic and combined approach based on the ODAT, MDAT and RAAP analyses, as a first initiative of such analysis at a European scale. The key messages of the analyses results are presented below.

8.2.2 The One-Driver-At-a-Time (ODAT) approach: Sensitivity analysis

The first part of the thesis investigated the sensitivities of future cross-sectoral impacts considering a wide range of climatic and socio-economic drivers. The focus was on investigating the complex interactions among various sectors/sub-systems to better understand how changes in individual drivers will affect Europe's future landscape change dynamics. The ODAT-based sensitivity analysis was applied to investigate the direct and indirect implications of various future changing conditions, which cross sectoral and regional boundaries. The analysis allowed to track if, and how, the effects of one driver on a sector/sub-system or region are transferred and felt by other sectors/sub-systems or regions in order to identify: (1) those sectors/sub-systems and regions most sensitive to future changes (i.e., which sector/sub-system and region gain or lose under a given change of driver), (2) the mechanisms of sensitivity (i.e., whether the effect of the drivers on the sectoral indicators is direct, indirect or combined), (3) the trends/directions of sensitivity in terms of the influence of each driver on sensitivity of the indicators (i.e., whether an increase in a driver contributes to an increase (positive effect) or decrease (negative effect) in the indicator), (4) the form/nature of sensitivity (i.e., linearity/non-linearity of the relationship for each driver-indicator combination), (5) the magnitudes of sensitivity (i.e., whether the percentage change in indicators under change in the drivers is strong, weak or insignificant change), and (6) the relative importance of the various key climatic and non-climatic drivers across the sectors/sub-systems and regions.

The results are complex (Chapter 5). The ODAT analysis demonstrates that most sectors/sub-systems are either directly or indirectly sensitive to a large number of drivers (20 out of 25 drivers considered). Over thirteen of these drivers have indirect impacts on all sectors/sub-systems (except flooding and urban), while only four drivers have indirect effects on flooding. In contrast, for the urban sector/sub-system all the drivers are direct. Moreover, most of the driver–indicator relationships are non-linear, and hence there is the potential for 'surprises'. The analysis provided a better quantification and increased understanding of the complex relationships between the various input variables and outputs parameters within the IAP. This is crucial for providing a better understanding of such complex models and future predictions of impacts in a world where both climate and socio-economic conditions are changing together. These are investigated using the MDAT-based scenario and uncertainty analysis, and the key results and conclusion are presented and discussed below.

8.2.3 The Multiple-Drivers-At-a-Time (MDAT) approach: Scenario and uncertainty analysis

Following the ODAT analysis, a screening criterion for drivers with a 'strong' and 'non-linear' effect on more than one sector/sub-system at the European scale (see Tables 5.3 and 5.4) has been used to identify the key climatic and socio-economic drivers with important cross-sectoral implications (Section 4.5). The study identified eight key factors representing (1) four climatic drivers: (i) temperature, (ii) summer precipitation, (iii) winter precipitation, and (iv) CO_2 concentration; and (2) four socio-economic drivers: (i) population, (ii) GDP, (iii) food imports, and (iv) agricultural yields. Considering thousands of scenario realisation of the combination of these drivers, the MDAT analysis investigated the key sensitivities and uncertainties of the potential cross-sectoral impacts due to uncertainties of future climate and socio-economic changes considering the 'full' and 'plausible' sample scenario ranges (Chapter 6). The analysis focussed on quantitative estimates of the: (i) statistical significance of the mean changes in indicators from baseline estimates, (ii) sensitivities of the indicators under changes in the various key climatic and socio-economic change scenarios, (iii) uncertainties of the cross-sectoral impacts due to uncertainties of climate change and socio-economic change, and (iv) the spatial distribution and pattern of the changes in indicators across the scenarios, and finally (v) identification of the key scenarios that represent the extreme uncertainty boundaries of the potential cross-sectoral impacts, which are used for assessing the potential cross-sectoral implications (in terms of synergies, conflicts and trade-offs) and robustness of future adaptation policies (which is discussed below in Section 8.4).

The analysis provided new quantitative insights into the complex interactions of Europe's FWLE nexus and associated key sensitivities and uncertainties of the potential cross-sectoral impacts under deep uncertainties. Based on the MDAT analysis, a number of high level outputs have emerged: (i) food production is likely to be the dominant driver of Europe's future landscape change dynamics (even without climate change), (ii) agriculture and other land use allocation are driven by complex interactions and feedback across various sectors/sub-systems, (iii) and hence, there are no clear patterns/trends in future food production under most of the various climate scenarios, (iv) these changes have significant knock-on implications for other sectors/sub-systems such as forestry (timber production), biodiversity, and water, and (v) while there are clear trends/signals for biodiversity, water and flooding impacts, (vi) future changes in urban areas (i.e., artificial surfaces) are relatively small in comparison with other sectors/sub-systems. Furthermore, the results also highlighted that the combined effects of climatic and socio-economic factors are not always linear (i.e., simple addition of individual impacts), demonstrating the potential non-linear amplifications of future impacts under some scenarios, with varied effects across sectors/sub-systems and regions (Section 6.5.1). As a result, future adaptation gets more complicated due to the complex interactions between the nexus systems and associated non-linearities, even without climate change. Hence, long-term planning of robust future adaptation (as well as mitigation) policies needs to take into account such sensitivities and uncertainties.

8.2.4 Robustness assessment of adaptation policies (RAAP)

The RAAP analysis explored the robustness of four classes of adaptation policy options in terms of the potential benefits and associated synergies and trade-offs in reducing potential future impacts under various climate and socio-economic change scenarios following the method by Jager *et al*. (2015). The assessment was based on a comparison of the cross-sectoral impacts 'without' (i.e., potential impacts) and 'with' (i.e., residual impacts) adaptation across the various sectors/sub-systems, regions, and scenarios (Section 4.6). The four adaptation policy options considered are: (i) *Behavioural adaptation* (BA) – which focuses on improving human and social capitals (e.g., using education and awareness-raising), (ii) *Environmental adaptation* (EA) – which focuses on improving natural capital (e.g., protecting and creating space for the environment to improve the health of ecosystems and habitats), (iii) *Technological adaptation* (TA) – which focusses on improving manufactured capital (e.g., using technology advancements), and (iv) *Combined adaptation* (CA) – which focusses on improving all capitals by combining measures from the above three policies. The analysis focussed on a total of 34 different scenarios. The scenarios were identified following the MDAT analysis, as those that cover the extreme uncertainty boundaries of the cross-sectoral impacts for each of the seven selected sectoral indicators at the European scale.

The results demonstrate that the largest benefit of adaptation is estimated for the forest sector/sub-system, with up to a 12-fold increase in timber production under the CA policy, particularly under the climate scenarios (Section 7.3.2). In contrast, for the urban sector the effects are relatively very small. Comparing the results across the sectors/sub-systems and regions, all except the CA policy shows robustness with respect to the geographical scale, in terms of improving all sectoral indicators across all the five regions under at least one scenario. For example, under three of the socio-economic scenarios, all sectors/sub-systems improve across all regions under the TA policy. Similarly, all sectors/sub-systems show improvement across all the five regions under the BA policy and one of the socio-economic scenarios, while improving under the EA policy in one of the four extreme climate and socio-economic change combined scenarios. However, although there is robustness for at least one sector/sub-system with respect to the geographical scale, the results show that there is no robustness across the sectors/sub-systems under any of the adaptation policies in all the climate scenarios. The sectoral robustness of each of the four adaptation policies based on ranking of the % change in the indicators with adaptation (relative to impacts without adaptation) across the regions and scenarios is discussed in detail in Section 7.3.2.

8.2.5 A nexus-based conceptual framework for long-term adaptation planning

Following examination of the CLIMSAVE IA methodology and a review of existing integrated frameworks, a new nexus-based conceptual framework has been developed for informing a long-term and multi-/cross-sectoral adaptation planning under uncertainty. Detailed description of the framework is presented in Section 7.3.3. Unlike existing frameworks, the new framework provides an integrated perspective on conceptualising the following five key hierarchal questions that need to be addressed in the design and development of future systems integration modelling approaches and assessment tools that support cross-sectoral adaptation policy decisions:

(i) What are the main sectors/sub-systems that represent the coupled human-nature systems?

(ii) What are the key drivers of change in the nexus systems?

(iii) Which cross-sectoral impacts and adaptation indicators/metrics are more relevant for stakeholders and policy-makers?

(iv) Which interactions within and across the nexus systems are more important?

(v) How can we design robust and multi-sectoral adaptation policies across sectors/sub-systems, scales, and scenarios?

Quantification of the framework will help address these important questions by identifying and focussing on the key components of the socio-economic and environmental systems and their connections for improved understanding of the interdependencies and associated synergies, conflicts and trade-offs between the various nexus systems. Such information is crucial for decision-makers to device appropriate multi-/cross-sectoral adaptation policies that maximise synergies (benefits) and minimise conflicts (unintended negative consequences).

8.2.6 Limitations

The first point to highlight is that the research is based on CLIMSAVE's representation of Europe's FWLE nexus, hence limited to its key assumptions (discussed below). In addition, the overall methodology (Figure 4.1) used in the ODAT and MDAT analyses has focussed on selected sectoral indicators (one from each sector/sub-system) and hence does not cover all the output variables of the sectors/sub-systems integrated within the CLIMSAVE IAP. Hence, the results presented here may not, inherently, reflect responses of the sectors/sub-systems entirely. While there is a pragmatic reason behind such focus on specific indicators, future work can also consider wider ranges of policy-relevant impact metrics for a better understanding of the sectoral and cross-sectoral responses and associated adaptation needs under uncertainties of future climate and socio-economic changes. In addition, the following sub-sections present some of the specific potential improvements of the research focussing on: the CLIMSAVE methodology in general, and the ODAT (sensitivity), MDAT (scenario and uncertainty), and RAAP (adaptation robustness) analyses methods.

Limitations of the CLIMSAVE integrated assessment methodology

Detailed description of the key potential improvements of the CLIMSAVE IAP is presented in Section 7.4.2. However, one of the main aspects of the CLIMSAVE integrated modelling framework worth stating here again is that its rural land use allocation model uses an autonomous adaptation, which prioritises food production based on a selected optimisation algorithm. Hence, the analysis results presented in this thesis depend on this assumption and demonstrate that Europe's future land use could be mainly driven by change in food production and associated agricultural land use. This is a key assumption in that food security is considered as the primary challenge in future development and climate policy plans in Europe. The research highlighted that given the assumption on prioritising food production, understanding the FWLE nexus plays an important role in devising appropriate adaptation to future changing conditions. In addition, it also highlighted that the challenge for future adaptation will get more complicated (even without climate change) due to the complex interactions and associated synergies, conflicts and trade-offs between the various socio-economic and environmental systems that cross traditional sectoral and regional boundaries. Future uncertainties of climate change (e.g., temperature, precipitation, CO_2 concentration, etc.) and socio-economic change (e.g., population, GDP, oil price, etc.) will also add to this challenge. However, although the food prioritisation is a realistic assumption as food security raises an important challenge in Europe under future climate and socio-economic change scenarios, further improvements of the CLIMSAVE integrated methodology could re-evaluate the assumption in order to explicitly understand impacts of the key drivers of future land use change with and without adaptation. This will allow investigation of uncertainties of the potential cross-sectoral impacts associated with the various climatic and non-climatic drivers so that the key FWLE nexus trade-offs can be explicitly evaluated. This will help identify future cross-sectoral adaptation needs in order to devise appropriate response strategies that maximise benefits and minimise trade-offs between the various nexus systems and adaptation policy options.

Limitations of the ODAT sensitivity analysis approach

The first part of the thesis used the ODAT approach by varying one variable at a time while keeping other input parameters at the baseline in order to investigate key sensitivities of the selected sectoral indicators to future changes in individual climatic and socio-economic drivers. The results help identify and quantify the complex relationships between the various drivers (i.e., input variables) and sectoral indicators (i.e., output parameters). This provides an important platform to understand and better interpret outputs of such complex IAMs and associated scenario and uncertainty assessments that are based on change in multiple drivers. Such an approach provides a simplified approach to identify the most important parameters/assumptions and provide broad insights into how different assumptions affect future choices. While such a sensitivity analysis has these and various other advantages, especially when dealing with such complex IAMs, the ODAT approach could be further improved on those limitations both inherent to the approach itself as well as associated with the CLIMSAVE integrated modelling assumptions, as the one at a time approach may miss potential key sensitivities. Two examples of such missing sensitivities that were not picked up by the ODAT approach are highlighted here. Firstly, the direct (on urban) and indirect (on flooding) sensitivities associated with the three drivers that affect the spatial pattern of artificial surfaces (i.e., household externalities preference, compact vs sprawl development, and attractiveness of the coast) (Table 4.2) were identified as with no/insignificant cross-sectoral effect (Table 5.4). This is due to the fact that the effect of these drivers is linked to the effect of other factors that drive the changes in magnitude of artificial surfaces (e.g., population and/or GDP changes). Secondly, due to the implicit in-built adaptation considered within the rural land use allocation model (i.e., prioritising food production), under the ODAT approach food production is mostly less sensitive to changes in individual drivers as the model tries to maintain food production to meet demand by autonomously adapting through, for example, expansion of agricultural land. This has indirect impacts on all other sectors/sub-systems that are dependent on land use (e.g., forestry and biodiversity). These limitations are addressed in the MDAT analysis (Chapter 6). In addition, the ODAT analysis focussed on aggregated results for the five regions considered, and hence it is worth noting that the results presented here may not fully reflect the spatial variations of the sensitivities within each region. This is also partly addressed in the MDAT analysis by assessing the spatial distributions of impacts based on the grid-based results (Sections 6.3–6.5, 6.7, and 6.8).

Limitations of the MDAT scenario and uncertainty analysis approach

While the MDAT analysis allowed exploring wide ranges of non-overlapping (which can be the case in the traditional scenario analysis approaches based on limited number of scenarios) scenario realisation combinations of the key drivers (identified in the ODAT analysis), some limitations remain. For example, future assessments could consider the following two potential improvements: (i) the analysis focussed on the scenario combinations of eight drivers (4 CD and 4 SED) selected based on their 'strong' and 'non-linear' impacts for more than one sector/sub-system at the European scale (Tables 5.3 and 5.4), however other drivers may have higher regional implications than those considered, and (ii) in comparison with the ODAT approach, the MDAT analysis involves a large number (thousands) of model runs requiring significantly more effort than for the ODAT approach (hundreds) (which also highlights the challenge associated with handling of such complex integrated model outputs and the need for the development and use of advanced data handling approaches, such as the emerging 'Big Data' technologies in terms of applying efficient data storage, querying and mining techniques).

Limitations of the adaptation robustness assessment

The main limitations of the robustness assessment of adaptation policies (RAAP) include: (i) the robustness assessment uses '% change of the indicators' as evaluate representation of the benefits of the various adaptation strategies. However, the use of a standardised common metric across the sectors/sub-systems (such as number of vulnerable people, e.g., Jäger *et al*. 2015 or monetary value of impacts, e.g., Ciscar *et al*. 2011) can provide a consistent measure of the benefits of adaptation for a better comparison of robustness of the policy options across the sectors/sub-systems; and (ii) the assessment focussed on 34 different scenarios (that are selected following the MDAT analysis), which represent the extreme uncertainty range of the various sectoral impacts at the European scale. While this consideration is consistent with the European scale focus of the thesis to demonstrate the relative importance of various adaptation policy options across the sectors/sub-systems, regions and scenarios considered, it is worth noting that other MDAT scenarios that are not part of the selected 34 scenarios may have higher regional implications than those results presented here. Hence, future work could also improve on this.

8.3 Recommendations for Further Research

The following sections present future research directions in terms of informing future: (i) improvement of the CLIMSAVE integrated platform, and (ii) development of the next generation of IAMs. In addition, further research could also consider addressing the various limitations outlined above for informing the development of systematic approaches that facilitate wider application as well as policy-relevance of such complex assessment models for informing long-term planning of adaptation as well as climate mitigation policies in a wider context of addressing global sustainability issues.

8.3.1 Improving the CLIMSAVE integrated methodology

Despite the various key features (outlined in Section 7.4.1), the study also highlighted that the CLIMSAVE IAP, as is the case with such complex integrated models, also has some limitations. Hence, future improvement of the IA platform needs to take into account the limitations that are listed below (Section 7.4.2 for more details):

- Incorporating missing links and dynamic feedbacks between the sectors/sub-systems,
- Adding other important sectoral components of the socio-ecological systems nexus (e.g., energy, health sectors/sub-systems, etc.),

- Refining the selection of sectoral and cross-sectoral indicators/metrics based on stakeholder needs and relevance for adaptation,
- Considering consistent representation of sectoral processes combined with similar level of complexity between the various sectoral models,
- Improving on the issues of scale (both spatial and temporal),
- Improving on flexibility of the integrated platform to allow running sectoral models in both linked and unlinked mode,
- Adding capability for automated multiple integrated model runs in batch version on the web,
- Translating the IAP from exploratory to decision support tool,
- Updating the climate and socio-economic scenarios with the latest RCPs and SSPs,
- Considering dynamic implementation of adaptation taking into account changes in adaptation over time and associated feedbacks.

In addition to the various limitations of the integrated platform, important potential future improvements in the individual sectoral models have also been identified (Section 7.4.2). It is also worth highlighting that in addition to improving future versions of the CLIMSAVE IAP, improving the various sectoral model limitations presented here could also help inform the development of future IAMs that are also based on similar ‘multi-models coupling’ modelling approaches.

- *Urban model*: (i) considering climate change factors, (ii) taking into account feedbacks with the flood model, (iii) improving ‘growth-only’ assumption, (iv) improving spatial pattern change analysis algorithms, and (v) improving look-up tables by introducing interpolation modules.
- *Flooding model*: (i) improving coastal flood module by moving from ‘step-change’ to ‘regression’ based topographic data representation, (ii) improving fluvial module by taking into account seasonal variability of river flood flows, (iii) improving impact metrics/indicators by moving from event-based to risk-based analysis (e.g., expected annual number of people flooded), and (iv) incorporating other flooding mechanisms (e.g., pluvial, and groundwater flooding).
- *Agriculture model*: (i) improving the in-built ‘autonomous adaptation’ assumption, (ii) improving linkages with forestry (in terms of land use prioritisation) and water (in terms of irrigation water use allocation and availability) models, and (iii) considering associated feedback mechanisms (e.g., with forestry).

- *Forestry model*: (i) improving forest species database, (ii) improving future projection algorithm in terms of taking account of (a) changes from one species to another, (b) planting new species in areas where there is none, (iii) improving feedbacks with land use model, also taking account of socio-economic factors.
- *Water model*: (i) improving spatial data downscaling (e.g., river basin scale data to 10'x10' grid resolution), (ii) improving temporal data downscaling (e.g., monthly precipitation data to daily river discharges), (iii) integrating agricultural sector/sub-system holistically and improving associated feedbacks, and (iv) improving feedbacks between biodiversity model, in terms of capturing future changes in minimum environmental flow requirements.
- *Biodiversity model*: (i) improving selection of representative species groups, and (ii) capturing feedbacks with other sectors/sub-systems.

8.3.2 The road ahead for the next generation of IAMs

Following a review and appraisal of existing integrated modelling approaches and tools and evaluation of the CLIMSAVE IAP, a number of potential future directions for improving systems integration approaches are identified. In addition to the various factors discussed as part of improving the CLIMSAVE IAP (Section 7.4.2), a number of important factors in informing development of the next generation of IAMs are also identified (Section 7.5 for details). These factors need to be considered for advancing systems integration and modelling approaches more generally in order to enhance relevance of IAMs for informing adaptation as well as climate mitigation policies and resources management decision-making processes at appropriate scales, framed in the context of devising global sustainability solutions:

- Integrating more socio-ecological sectors/sub-systems simultaneously and more comprehensively,
- Identifying and focusing on the most important components and their interactions within each sector/sub-system integrated,
- Identifying and quantifying both direct and indirect key linkages (point of contact) and interactions between systems,
- Identifying and explicitly taking account of feedbacks between systems,
- Integrating multiple spatial, temporal, and organisational scales,
- Considering both climatic and socio-economic change drivers holistically,
- Incorporating adaptation and mitigation policies explicitly and dynamically,
- Integrating explicit treatment of uncertainty,
- Improving on existing integrated frameworks and developing and applying new tools, and

- Designing IAMs as decision-support tools for translating findings into policy and practice.

8.4 Final Concluding Summary

Food, water and land systems interact with each other and with natural ecosystems in complex and potentially unexpected ways under uncertain changing conditions. These interactions and associated trade-offs will have important implications for the well-being of human societies and health of natural systems. A sustainable use and management of these resources as well as future socio-economic development planning requires: (i) a holistic understanding of these socio-ecological nexus system interactions and feedbacks, (ii) assessment of the key sensitivities and uncertainties of potential cross-sectoral impacts under changing future climate as well as social, economic, technological, environmental and policy governance settings, and (iii) devising appropriate adaptation (and mitigation) policies framed in the context of global sustainability. A nexus-based application of IA modelling approaches and tools can provide important insights in facilitating this. This thesis presented a systematic methodological framework based on an extensive application of one IAM, the CLIMSAVE IAP to provide a better understanding of the FWLE nexus at the European scale and identification of potential areas of improvement of the IAP to inform development of the next generation of IAMs. A summary of the key final concluding remarks are listed below:

- Eight of the 25 (climatic/socio-economic) drivers are identified as key parameters at the European scale, with important cross-sectoral implications for the FWLE nexus (i.e., with 'strong' and 'non-linear' impacts on more than one sector/sub-system):
  - ✓ Four climatic drivers: *temperature, winter and summer precipitation, and* CO_2 *concentration*
  - ✓ Four socio-economic drivers: *population, GDP, food imports, and agricultural yields*
- Considering a wide range of scenario combinations of the above key drivers, the results demonstrate that:
  - ✓ Food production is likely to be the main driver of Europe's future landscape change dynamics, even without climate change.
  - ✓ Agriculture and land use allocation in general is often driven by complex interactions between various sectors/sub-systems.
  - ✓ There are no clear patterns/trends in future food production under most climate scenarios.

    - ✓ Agricultural changes have significant knock-on effects on other sectors/sub-systems, such as forestry (i.e., timber production), biodiversity, and water.
    - ✓ There are consistent trends for the biodiversity, water and flood impacts under most scenarios, with regional variations.
    - ✓ In contrast, future changes in urban areas (in terms of artificial surfaces) at the European scale are found relatively small.
- o Combined effects of climatic and socio-economic factors are NOT always 'additive', suggesting the potential for non-linear amplifications of future impacts across sectors/sub-systems and regions.
- o Consequently, making the right adaptation policy choices is complicated, even without climate change, due to the complex nexus interactions and associated non-linearities, highlighting:
    - ✓ The need for a better understanding of the nexus interactions and potential cross-sectoral trade-offs under various adaptation options, and
    - ✓ The role of such systematic analysis in providing important insights for decision-makers to devise robust adaptation policies that maximise synergies (benefits) and minimise conflicts (unintended consequences).
- o Despite the significant progress in integrated assessments/modelling approaches over the last several decades, some challenges still remain, e.g., in translating IAMs from exploratory to decision support tools for informing robust adaptation (as well as mitigation) policies. However, with the rapidly increasing computational resources and data availability, future advances in systems integration approaches could build on existing integrated modelling frameworks and tools to better inform development of the next generation of IAMs, while balancing use-prohibiting complexity with required accuracy.

APPENDICES

A. Review of IA Modelling Approaches and Frameworks for Climate Change Impacts and Adaptation

Integrated Assessment Studies/ Models	Scale of Assessment	Method (*Models*) and Drivers Considered	Sectors/Sub-systems and Impact Indicators Considered	Strengths/Limitations	Relevant Example References
REGIONAL/CONTINENTAL Scale Assessments					
Africa:					

Asia:					
AIM (***The Asia-Pacific Integrated Model***)	Spatial: ▪ Regional/National (and province) (5° lat. x 5° long. grid, but with variable input data resolution, e.g., 5' lat. x 5' long. grid for soil, 0.5° lat. x 0.5° long. climate data and country/province level for environmental and socio-economic data) Temporal: ▪ 1990–2100 (with 5 year time-step)	▪ A large scale computer simulation model developed for the Asian-Pacific region ▪ Integrates more than 20 models grouped into three main models: the GHG emission (AIM/Emission), the global climate change (AIM/Climate), and the climate change impact (AIM/Impact) models from climate policy assessment viewpoint ▪ Include direct (surface water runoff/transport, crop productivity, vegetation, and infectious disease models) which are linked to indirect (global agricultural trade model and a national level macro-economy) impact models ▪ Uses a detailed GIS environment for presenting spatial distribution of impacts	Sectors/Sub-systems: ▪ Agriculture, ecosystems, human health, water Impact indicators: ▪ ***Bio-physical***: change in surface runoff, soil moisture, evapotranspiration, and river discharges; change in forest regions ▪ ***Socio-economic***: crop productivity changes (*direct* and *indirect*) (e.g., rice, winter wheat, maize), malaria risk change	Strengths: ▪ Allows to assess alternative climate policies ▪ Contains a very detailed technology selection modules to evaluate the effect of introducing advanced technologies ▪ Stakeholder integration ▪ Multi-scale application Limitations: ▪ Advanced skill requirement for running the tool ▪ Data and power intensive simulation requirement ▪ Coarse spatial resolution ▪ More focus on mitigation policies rather than adaptation ▪ PC-based tool and not available to public	Kainuma *et al*. 2003; Matsuoka *et al*. 2001; Morita *et al*. 1994
IAM (***Integrated Assessment***	Spatial: ▪ National/China (60km x 60km)	▪ Combines 3 climate and 3 socio-economic scenarios with 3 levels of adaptation measures	Sectors/Sub-systems: ▪ Flooding, agriculture, biodiversity, and water	Strengths: ▪ A first national initiative which provides a better understanding of	Li *et al*. 2002;

Model for Agriculture in China)	<u>Temporal</u>: ▪ 2000–2050 (using snapshots of 2020s & 2050s)	▪ Integrates: crop choice, pest and diseases, soil-carbon, crop, biodiversity, and water resource models ▪ Uses a GIS interface to facilitate integration of sectoral analysis, and also for visualisation and presentation of results	<u>Impact indicators</u>: ▪ ***Bio-physical***: agricultural area, soil quality, irrigation demand ▪ ***Socio-economic***: crop yield change, production	indirect impacts and effects of different adaptation measures ▪ Adaptation considered implicitly <u>Limitations</u>: ▪ Limited stakeholder integration ▪ Lack of public availability of the tool ▪ Advanced skill requirement for running the tool ▪ Coarse resolution	
Europe:					
ACACIA (*A Concerted Action towards a comprehensive Climate Impacts and Adaptations assessment for the European Union*)	<u>Spatial</u>: ▪ European level (variable grid resolution per sector/sub-system but the climate model uses 2.5° lat. x 3.75° long. resolution) <u>Temporal</u>: ▪ present-day and future period of 2020–2080 (considering snapshots of 2020s, 2050s and 2080s)	▪ An expert review of current knowledge, drawing upon all available knowledge including the most up-to-date projections of likely future climate change ▪ Considers effects of weather now, future socio-economic and technological scenarios, and climate scenarios ▪ Uses European scenarios developed on the basis of the UKCIP and SRES approaches ▪ Integrates 5 different climate models (*CGCM1*, *CSIRO-Mk2b*, *ECHAM4*, *GFDL-R15*, *HadCM2*)	<u>Sectors/Sub-systems</u>: ▪ Water, soil and land, ecosystems, forestry, agriculture, fisheries, insurance, transport and energy, tourism and recreation, health, coastal zones, mountain regions <u>Impact indicators</u>: ▪ ***Bio-physical***: changes in hydrological system, land use change, salinization, peat wastage, soil erosion, change in ecosystem productivity, draught and forest fires, change in aquatic biodiversity, saltmarsh and intertidal habitats ▪ ***Socio-economic***: change in water quality and supply, stress on irrigation use, flood risk to people and economic damage, change in crop production and livestock systems, change in fish production, flood impacts on insurance, tourism, health issues	<u>Strengths</u>: ▪ Provides a comprehensive review of a wide range of sectoral impacts of climate change, with a particular focus on identifying key issues for policymakers, planners and researchers. <u>Limitations</u>: ▪ Lack of quantitative consideration of interactions and feedbacks between sectors/sub-systems (only qualitative implications are considered) ▪ Some sectoral assessments mainly relies on expert judgment ▪ Inconsistency between the scenarios used across different sectors/sub-systems (or sectoral models) considered ▪ Climate and socio-economic scenarios are treated independently, rather than holistically	Arnell 2000; Bindi and Olesen 2000; Hulme and Carter 2000; Jordan *et al*. 2000; Nicholls 2000; Parry 2000a,b; Rounsevell and Imeson 2000;
ACCELERATES (*Assessing Climate Change Effects on Land use and Ecosystems:*	<u>Spatial</u>: ▪ European/ Regional (NUTS regions) (10' lat. x10' long. resolution) <u>Temporal</u>:	▪ The climate (CC) and socio-economic change (SE) scenarios used are associated based on internally consistent assumptions about the effects of SE drivers on CC ▪ Uses a conceptualized linkage between agricultural land use (which *combines*	<u>Sectors/Sub-systems</u>: ▪ Agricultural land use and biodiversity <u>Impact indicators</u>: ▪ ***Bio-physical***: changes in area of intensive, extensive, and abandoned land, as a function of farmer profit; and species	<u>Strengths</u>: ▪ Allows to compare vulnerability across the two sectors/sub-systems considered taking into account both direct and indirect impacts ▪ Highlights the importance of sectoral integration in policy development	Audsley *et al*. 2006; Berry *et al*. 2006; Harrison *et al*. 2006; Rounsevell *et al*. 2006

***from Regional Analysis to the European Scale*)**	▪ 2000–2080 (using snapshots of 2020s, 2050s, 2080s)	*ROIMPEL and SFARMOD models*) and species (*SPECIES model*) for a combined vulnerability assessment approach	vulnerability as a function of changes in suitable climate space (area of new climate space, overlap between current and new climate space, lost climate space, future suitable climate space) ▪ ***Socio-economic***: vulnerability of suppliers (farmers and also retailers and people involved in ancillary agro-industries) and consumers (of agricultural goods (food & fibre) or services (landscape and environmental externalities))	and implementation ▪ Adaptation considered ▪ Stakeholder integration **Limitations**: ▪ Interactions and feedbacks between sectors/sub-systems are not dynamic – as independent model outputs are shared between sectors/sub-systems ▪ Limited to two sectors/sub-systems only ▪ Limited treatment of uncertainty ▪ PC-based component models and not available freely	
CLIMSAVE (*CLimate change Integrated assessment Methodology for cross-Sectoral Adaptation and Vulnerability in Europe*)	**Spatial**: ▪ European (10’ lat. x 10’ long. resolution) & National/Scotland (5km x 5km resolution) **Temporal**: ▪ 2010-2050 (using snapshots of 2020s and 2050s)	▪ A European scale further extension of the concept and methodology of the RegIS tool ▪ A user-friendly, interactive web-based assessment tool: which include four screens which allow assessment of: **Impacts**, **Vulnerability**, **Adaptation**, and **Cost Effectiveness** ▪ Integrates 5 different climate models (*HadGEM*, *GFCM21*, *IPCM4*, *CSMK3*, *MPEH5*) with stakeholder-led CLIMSAVE socio-economic scenarios (including user-defined scenarios) and wide range of adaptation measures ▪ Integrates 9 different sectoral impact models: *meta-RUG*, *meta-CropYield*, *meta-Pest*, *meta-GOTILWA+*, *meta-SFARMOD*, *WaterGAP meta-model*, *Coastal-Fluvial Flood (CFFlood) model*, SPECIES, *meta-LPJ-GUESS*, *meta-SnowCover* ▪ Each sectoral model uses different meta-modelling approaches, including: *look-up tables*, *artificial neural networks*, *soil/climate clustering*, *3D surface*	**Sectors/Sub-systems**: ▪ Agriculture, biodiversity, coasts, forestry, urban development, water resources and use **Impact indicators**: More than 170 output parameters, representing: ▪ ***Bio-physical***: change in areas of artificial surfaces (residential and non-residential), crop yields and total production, wood yield, biomass and food energy, areas of intensively and extensively farmed and forested and abandoned land, water availability; area at risk of fluvial and coastal flooding, areas of wetland habitats; biodiversity species distributions (present/absence) and net primary production, etc. ▪ ***Socio-economic***: Flood impacts on people and economic damages, net primary production (NPP), food production, timber production, etc. (detailed list can be found in Holman and Harrison (2012)	**Strengths**: ▪ Tool publicly available online ▪ Interactive and user-friendly ▪ Stakeholder integration at various stages of model development ▪ Greater consideration of cross-sectoral linkages and feedbacks by integrating six different key sectors/ sub-systems ▪ Spatially explicit with more detailed spatial resolution than previous studies ▪ Consideration of the combined effect of both climate and socio-economic change drivers ▪ Adaptation considered ▪ Allows uncertainty and sensitivity analysis to be undertaken ▪ Multi-scale application: both at a continental scale (Europe) and regional scale (Scotland) **Limitations**: ▪ More sectors/sub-systems could have been added, e.g., health, energy, tourism, etc.	Harrison *et al*. 2012; www.climsave.eu

		response diagrams, and a *simplified process-based modelling approach*		▪	
PESETA (*Projection of Economic impact of climate change in Sectors of the European Union based on boTtom-up Analysis*)	**Spatial**: ▪ European/ Regions/National (the climate model uses a 50km x 50km resolution; the impact models' resolutions vary across sectoral impact models) **Temporal**: ▪ Using snapshots of the 2020s and the 2080s	▪ Integrates a consistent and high time-space resolution climate data, physical impact-specific models, and a multi-sectoral computable general equilibrium (CGE) economic model ▪ Assesses the monetary estimates of impacts of climate change – in terms of overall order of magnitude and distribution (across space, time and sector/sub-system) on overall economy ▪ (The bio-physical impacts (outputs from each sector/sub-system) are used as an input to derive the GCE economic model to estimate monetary impacts of climate change in the European agricultural sector/sub-system – considering production, consumption and policy)	**Sectors/Sub-systems**: ▪ Agriculture, river floods, coastal systems, tourism, and human health **Impact indicators**: ▪ ***Bio-physical***: change in crop yield (agricultural land suitability and productivity), change in frequency and severity of river floods, impacts of sea floods ▪ ***Socio-economic***: change in international tourism flow (bed nights), flood (river and coastal floods) impacts on people and economic damage costs, heat and cold-related mortality; change in consumer welfare and GDP, and overall damages in EU in terms of GDP loss	**Strengths**: ▪ A broad overview summary of impacts across a wide range of sectors/sub-systems considered ▪ Both climate and socio-economic drivers considered ▪ Adaptation considered ▪ Stakeholder integration **Limitations**: ▪ Limited quantitative consideration of interactions and feedback between sectors/sub-systems ▪ A synthesis and data sharing of sectoral model outputs rather than a dynamic integration modelling across sectors/sub-systems ▪ Potential inconsistent in spatial resolution between sectors/sub-systems ▪ Limited treatment of uncertainty ▪ All component models are PC-based and no single interface/tool exists	Ciscar *et al.* 2011; Iglesias *et al.* 2009; Moreno 2009; Richards and Nicholls 2009; Watkiss *et al.* 2009
North America:					
IAM (*Integrated Assessment Model for the Conterminous USA*)	**Spatial**: ▪ National (USA) (resolutions vary across models, e.g., 204 four-digit basins for water model, and 1-100ha farm field agriculture model) **Temporal**: ▪ 1990-future time (future time	▪ Dynamic process-level understanding of cross-sectoral behaviour ▪ Integrates water resource (HUMUS – Hydrological Unit Model of the US) and crop production (EPIC – Erosion Productivity Impact Calculator), ecosystem (BIOME 3), and economic (AgLU – Agriculture and Land Use) assessment models. ▪ Uses two GCM-derived climate change projections – 12 climate scenarios, with a particular focus on extreme climate conditions	**Sectors/Sub-systems**: ▪ Agriculture, water resources, natural ecosystems, economics **Impact indicators**: ▪ ***Bio-physical***: change in distribution and productivity of unmanaged ecosystems ▪ ***Socio-economic***: change in dry land agriculture and crop production, change in water supply; change in irrigation demand, economic consequences	**Strengths**: ▪ Nationally improved methodology for integrated assessment of impacts ▪ Stakeholder integration **Limitations**: ▪ Relatively few number of sectors/ sub-systems ▪ Soft linking between some sectors/ sub-systems ▪ Only climate drivers are considered ▪ Adaptation is implicit or not considered ▪ Uncertainty is limited to climate	Edmonds and Rosenberg 2005; Thomson *et al.* 2005;

	period not specified)			drivers ▪ PC-based model and publically unavailable	
Oceania:					

South America:					

NATIONAL/REGIONAL (SUB-NATIONAL) Scale Assessments					
ClimAID (*Integrated Assessment for Effective Climate Change Adaptation Strategies in New York State*)	<u>Spatial</u>: ▪ Regional/Subnational (New York State, USA) (variable resolution per sector/sub-system) <u>Temporal</u>: ▪ 1980s–2100 (considering snapshots of 2020s, 2050s and 2080s)	▪ An integrated approach that combines aspects of a risk-hazard approach (visualise future damages) and policy approach (visualise desired future) ▪ Focusses on five integrating themes, including: climate, vulnerability, adaptation, equity and environmental justice, and economic costs, across a range of sectors/sub-systems. ▪ Key interactions and feedbacks are represented through the use of climate scenarios ▪ The climate change projections used are developed based on 16 global climate models and three emission scenarios	<u>Sectors/Sub-systems</u>: ▪ Water resources, coastal zones, ecosystems, agriculture, energy, transportation, telecommunications, and public health <u>Impact indicators</u>: ▪ ***Bio-physical***: land affected by coastal and inland flooding, loss of land due to shoreline erosion, loss of coastal wetlands, ▪ ***Socio-economic***: health impacts of heat waves and floods, loss of crop due to excess water and droughts, economic damage due to flooding, monetary costs of impacts and adaptation	<u>Strengths</u>: ▪ A range of sectors/sub-systems considered ▪ Adaptation considered ▪ Stakeholder interactions are taken into account <u>Limitations</u>: ▪ Mainly based on qualitative approach and soft linking of sectoral inventory assessments ▪ Focusses on climate drivers and scenarios only ▪ Uncertainties are considered for the climate drivers only	Rosenzweig *et al*. 2011;
CLIMPACTS system (*An integrated model for assessment of the effects of climate change on the New Zealand environment*)	<u>Spatial</u>: ▪ National (5km x 5km resolution) and Regional and site level (1km x 1km resolution) <u>Temporal</u>: ▪ 1990–2100 (variable resolution and model dependent)	▪ Integrates a global energy balance climate model (MAGICC), national climate scenario generator and sectoral impact models ▪ Integrates a range of crop simulation models including for pasture production, wheat and maize yield, kiwifruit phenology, and soil carbon ▪ Accounts for different scales of assessment: national with a focus on spatial application (e.g., changes in areas of suitability), specific sites with a focus on temporal applications (e.g., changes in risk), and regional with a focus on	<u>Sectors/Sub-systems</u>: ▪ Agriculture (arable crops: wheat and grain maize), natural vegetation (grasslands: pastures), horticulture (fruit crops: kiwifruit and apples), water balance, soils <u>Impact indicators</u>: ▪ ***Bio-physical***: environmental sensitivities to climate change in terms of changes in areas of suitability for agriculture ▪ ***Socio-economic***: changes in risk in productivity	<u>Strengths</u>: ▪ Provides flexibility in application (e.g., to be easily update to take account of scientific advances) ▪ Multi-scale nature, within a national context ▪ Adaptation is considered <u>Limitations</u>: ▪ Model availability for user ▪ Limited to few sectors/sub-systems only ▪ Focusses on climate drivers only ▪ PC-based tool ▪ Advanced skill requirement for	Kenny *et al*. 2001; Warrick *et al*. 2001 ; Ye *et al*. 1999;

		integration of both spatial and temporal applications		running the tool	
PRIMA (*Platform for Regional Integrated Modeling and Analysis*)	**Spatial**: ▪ Sub-/national (e.g., Midwest or eastern US) (resolutions vary across the component models) **Temporal**: ▪ 2010-future time (e.g., 2050)	▪ Uses flexible multi-model coupling approach ▪ Integrates several component models including: regional climate (RESM), regionalised IA (GCAM-USA), and various sectoral models (such as energy/electricity production & use (e.g., BEND), hydrology and water management (e.g., SCLM, WM), agriculture (combining EPIC & AgLU), and land use/land cover (LULCC), crop productivity (EPIC). ▪ Focusses on climate change/climate policy scenarios	**Sectors/Sub-systems**: ▪ Climate, energy, water, and agriculture **Impact indicators**: ▪ ***Bio-physical***: weather prediction, terrestrial ecosystems, changes in tropical cyclone intensifications ▪ ***Socio-economic***: building energy demand, electricity supply and demand, demand and supply of agricultural crops, land use/land cover change, water supply and demand distribution	**Strengths**: ▪ Flexible, portable and modular – which can be applied to any region (if data available) ▪ Uses am open source approach which facilitate use by research and decision-making communities ▪ Explicit treatment of uncertainty ▪ Stakeholder integration **Limitations**: ▪ Relatively few number of sectors/ sub-systems ▪ Data and computational power intensive – large area scale applications could be challenging due to data limitations ▪ Adaptation is implicit or not considered	Kraucunas *et al*. 2015; Liu *et al*. 2015;
RegIS (*Regional Impact Simulator*)	**Spatial**: ▪ Regional/Local (i.e., East Anglia and North West England) (5km x 5km resolution) **Temporal**: ▪ 1990–2050 (using snapshots of 2020s & 2050s)	▪ A self-contained software tool designed specifically for the stakeholder community to be used on their own PC to investigate the sensitivity of an impact indicator, effects of future scenario uncertainty, and regional adaptive responses ▪ Integrates climate change and socio-economic scenarios together with stakeholder views ▪ Integrates different sectoral models including: soil/crop model, farm management model, coastal and river models, surface water nitrate catchment model	**Sectors/Sub-systems**: ▪ River and coastal flooding, agricultural land use change, coastal ecosystems, wetland habitats, and water resources **Impact indicators**: ▪ ***Bio-physical***: area at risk of flooding, change in areas of habitats (coastal and fluvial), change in area of land available for agricultural use, change in productivity, change in water resources (surface and groundwater), change in wetland species, and change in coastal habitats ▪ ***Socio-economic***: People affected by flooding, economic damages	**Strengths**: ▪ A first step toward a comprehensive integrated assessment approaches at a local scale ▪ Interactive and user-friendly ▪ Stakeholder integration ▪ Greater consideration of cross-sectoral linkages and feedbacks by integrating different sectors/sub-systems ▪ Spatially explicit with more detailed spatial resolution than previous studies ▪ Consideration of the combined effect of both climate and socio-economic change drivers ▪ Adaptation considered **Limitations**:	Audsley *et al*. 2002; Holman *et al*. 2002; Holman *et al*. 2005a,b; Holman *et al*. 2007; Holman *et al*. 2008a,b; Mokrech *et al*. 2008; Nicholls and Wilson 2001; Richards *et al*. 2008;

				▪ Publicly unavailable ▪ Skill requirement for running the tool ▪ Limited to local scale studies (but CLIMSAVE advances the methodology to a European level application)	
TaiCCAT (*Taiwan integrated research program on Climate Change Adaptation Technology*)	<u>Spatial</u>: ▪ National (Taiwan) <u>Temporal</u>: ▪ Considers	▪ Includes construction of system dynamics models of disciplinary sub-systems and integrates each sub-systems model to a cross-sectoral system dynamics model (e.g., TaiWAP model for assessing the vulnerability of water resource systems) ▪ Includes climate scenarios	<u>Sectors/Sub-systems</u>: ▪ Agriculture and biodiversity, energy and industry, water resource, infrastructure, public health, land use, environmental disaster, and coastal zones <u>Impact indicators</u>: ▪ ***Bio-physical***: not known yet? ▪ ***Socio-economic***: not known yet?	Note: Project is ongoing (2012 to 2015) – tool is being developed – benefit/limitation yet to be known	CEPD 2012; Liu *et al.* 2009
GLOBAL Scale Assessments					
DIVA (*Dynamic Interactive Vulnerability Assessment*)	<u>Spatial</u>: ▪ Global/Regional/ National/ Sub-national (e.g., Admin units) (uses about 12,150 variable length coastal segments (ranging between 9m and over 5200km, with an average segment about 85 km long) <u>Temporal</u>: ▪ Simulation time series between 1995-2100 (with 5 year time-steps)	▪ Uses a dynamic interactive modelling approach – which comprises a global database and a customised graphical user interface. ▪ The integrated model is developed following an iterative method consisting of a number of modules – using a common conceptualization of the system across disciplines (following the Open-GIS Abstract Specification of the Open GIS Consortium) ▪ The tool uses a segment representation of the world's coastline and associates up to 100 data values with each segment ▪ Major socio-economic drivers include: population, GDP, and land use change ▪ Main climate change driver: sea-level change	<u>Sectors/Sub-systems</u>: ▪ Coasts: Flooding, forest (in terms of area of forest and its monetary value), water (cost of salinization), ecosystem services (in terms of coastal and freshwater wetland habitats) <u>Impact indicators</u>: ▪ ***Bio-physical***: area of land loss (due to erosion, submergence), change in areas of potential floodplain and wetlands, coastal forest area ▪ ***Socio-economic***: flooding impacts on people, damage costs, adaptation (e.g., dikes and nourishment) costs, land loss costs, monetary value of habitats, etc.	<u>Strengths</u>: ▪ Dynamic and interactive integrated modelling approach ▪ Can be applied at a range of scales ▪ Considers both climate and socio-economic drivers ▪ Adaptation is considered ▪ Allows uncertainty and sensitivity analysis <u>Limitations</u>: ▪ Limited to specific sector/sub-system or region (i.e., focuses on coastal zones) ▪ Limited stakeholder integration ▪ PC-based software tool and some level of technical skilled required to use the tool, although without significant training ▪ Limited availability of the tool to end-users	DINA-COAST Consortium 2006; Hinkel *et al.* 2009; Vafeidis *et al.* 2008
ISI-MIP (*Inter-*	<u>Spatial</u>: ▪ Global (0.5^{o} x 0.5^{o}	▪ A multi-model assessments of impacts ▪ A community-driven modelling effort with	<u>Sectors/Sub-systems</u>: ▪ Agriculture, water, biomes, health (malaria),	<u>Strengths</u>: ▪ Provides a consistent framework as a	Frieler and the ISI-MIP

Sectoral Impact Model Intercomparison Project)	grid resolution) Temporal: ▪ 1971–2099 (with time slices of 2000, 2020, 2050 and 2085)	a goal of providing cross-sectoral global assessments ▪ Uses newly developed climate (Representative Concentration Pathways, RCPs) and socio-economic (Shared Socio-Economic Pathways, SSPs) scenarios ▪ Bringing together 38 impact models internationally across different sectors/ sub-systems, it systematically and quantitatively synthesises consistent climate impact data across sectors/sub-systems and scales	and coastal infrastructure (agro-) economic effects Impact indicators: ▪ ***Bio-physical***: runoff, discharge, potential evapotranspiration, irrigation water demand and consumption, livestock water withdrawal and consumption; biomes net primary production, biomass yield; crop yield, carbon mass storage in vegetation, ecosystem-atmosphere carbon flux; land use patterns, climatic suitability for malaria transmission, etc. ▪ ***Socio-economic***: population at risk from malaria; flood impact on people and cost of adaptations, etc.	first initiative to compare multi-model impact assessments across sectors/sub-systems and scales ▪ Offers an opportunity to analyse the origins of discrepancies between models for future improvement ▪ Limited stakeholder integration Limitations: ▪ Output data sharing between sectors /sub-systems rather than integration modelling (i.e., interaction between sectors/sub-systems) ▪ Relatively coarse spatial resolution, especially for local and regional scale applications ▪ Adaptation is not considered ▪ Treatment of uncertainty is limited to climate drivers ▪ PC-based (no single interface linking models and not available for public)	Team 2013; Warszawski *et al*. 2013;
SimCLIM (*A software modelling system for simulating bio-physical and socio-economic effects of climate variability and change*)	Spatial: ▪ Global to Local – it can be customised by user (Variable resolution using its custom-built GIS feature) Temporal: ▪ Variable time period and resolution (depending on input data and impact model being run)	▪ It is a flexible and 'open-framework' computer software modelling system package that links data and models to simulate impacts of climate variation and change ▪ Uses a 'pattern scaling' method to generate scenarios of future climate and sea-level changes ▪ Standard tools include: degree-day model, domestic water tank model, extreme event analyser, coastal erosion model, and data browser ▪ Describe baseline climates, examine current climate variability and extremes, generate climate and sea-level change scenarios	Sectors/Sub-systems: ▪ Agriculture, human health, coastal areas, and water Impact indicators: ▪ ***Bio-physical***: assess present and future climate risks (e.g., coastal flood risk (storm surge), drought risk (agricultural and water supply), risk of groundwater shortage, epidemic risk) ▪ ***Socio-economic***: assess present and future adaptation measures	Strengths: ▪ Open framework and allows users to customise the model and can be applied spatially to any geographic area and resolution depending on data availability and computational demands ▪ Stakeholder integration ▪ Adaptation is considered Limitations: ▪ Data and power intensive simulation requirement ▪ Limited number of sectors/sub-systems considered ▪ Focusses only on climate drivers and considers limited climate scenarios/models (e.g., sea-level rise scenario generator)	SimCLIM 2010; Warrick 2009; Warrick and Cox 2007; Warric *et al*. 2005

				▪ PC-based software and skill requirement for running the tool ▪ It is a commercial tool (not freely available)	

B. Ranges of Future Impact Projections for Scenario Implausibility Analysis: A Review of the Literature

The table below presents a summary of the literature review on future projections of the potential impacts on Europe's key land- and water-based sectors/sub-systems due to future changing climatic and socio-economic conditions. The review particularly focused on the minimum and maximum future projections of or related to the seven sectoral impact indicators (metrics) investigated in this study, which are: (i) *Artificial surfaces* (AS), (ii) *Biodiversity vulnerability index* (BVI), (iii) *Food production* (FP), (iv) *Land use diversity* (LUD), (v) *Number of people flooded in a 1 in 100 year (coastal and fluvial) flood event* (PF100), (vi) *Timber production* (TP), and (vii) *Water exploitation index* (WEI).

It is worth stating that (i) in the absence of a prior, consistently and clearly defined possible 'physical' (or 'plausible') ranges of the various indicators listed above, and (ii) due to the highly heterogeneous nature of the methods, spatial and temporal scales, metrics, scenarios used for future projections of the indicators assessed in various previous studies, important assumptions and simplifications have been made in order to obtain approximate ranges of future projections of the uncertainty of changes in the selected impact metrics. Therefore, it is worth highlighting that these projections are to be used as reference ranges of uncertainty of future projections for selecting a set of future scenarios that could considered as potentially 'not-implausible' sample scenario ranges identified from the 'full range' of the MDAT climate and socio-economic change scenarios investigated. Although it is important to recognise that such approach has its own limitations, the synthesis as a first step can provide a useful platform for capturing a wide range of diverse 'expert opinions' and uncertainties in future projections of the potential climate and socio-economic change impacts across the various sectors/sub-systems. While acknowledging these limitations, the synthesis also highlights the importance of potential future improvements in harmonising various detailed sector-specific and integrated studies across multiple sectors/sub-systems of a large system[28]. However, for the purpose of this analysis, the approach used (based on a synthesise of various future projections through a review of studies with comparable scales, scenarios, and metrics in order to identify the likely extreme ranges) has been considered sufficient as a basis for defining potential ranges of 'not-implausible' scenarios (including low- and high-end scenarios) in order to investigate the potential uncertainties in future projections of cross-sectoral impacts in Europe based on ensemble simulations under a range of plausible future climate and socio-economic scenarios. The various assumptions considered for each indicator in order to summarise consistent projections across the various studies (e.g., in terms of scenarios, baseline year, etc.) are also detailed in the table. The minimum and maximum projections from the various studies (based on different scenarios) are considered to identify the lower and upper limits across the studies, which are considered as plausible ranges for identifying the 'not-implausible' sample scenario ranges from the full ranges of the MDAT scenarios investigated within the thesis. A summary and percentile distribution of the ranges for the various indicators is presented in Chapter 4 (i.e., Section 4.3 and Figure 4.6).

Summary Table:

Impact Indicators/Metrics	Future Projections and Descriptions	References
Urban		
Artificial surfaces (AS)	▪ Total artificial surfaces (in urban, peri-urban, and rural areas) in 2000 is estimated as 168,478 km2 (4.7% of total area) and annual increase until 2025 is projected as: 1.09 (B2), 1.10 (B1), 1.55 (A2), and 1.86% (A1). *Assuming continuity of the current annual trends of these projections, the total % change in artificial surfaces relative to 2010 are estimated in 2050s: 1.8 (B2), 1.8 (B1), 3.0 (A2), and 3.8% (A1); and 2080s: 3.3 (B2), 3.4 (B1), 5.2 (A2), and 6.4% (A1).* ▪ The total (as % of initial year) (and annual rate of change in) artificial surfaces (for EU-28) during 1990–2000: 6.6% (0.657%/year) and 2000–2006: 3.84 (0.64%/year). *Assuming a continuation of the average growth trend, the % change relative to 2010 is estimated as 0.3% (2020s), 1.0% (2050s), and 1.7% (2080s).* ▪ Urban land use (% change during 2008–2025) projected between 7.9% (B1) and 9.9% (A1). *Assuming continuation of the average annual growth rates, the % change (as a proportion of area of Europe) in 2080s (relative to 2010) is estimated between +4.5% and +5.2%.*	▪ Piorr *et al*. (2011) ▪ EEA (2010) ▪ Boitier *et al*. (2008)

[28] This is also one of the main objectives and challenges of such integrated and cross-sectoral assessment, as in the case in the CLIMSAVE project and the analysis in this study.

	▪ Urban areas are projected to increase their share of European land stock by 1% by 2020. *The % change assuming extrapolation of these changes to 2080s (relative to 2010) is estimated at 5.4%*. ▪ Change in urban areas (as percentage of total European land area) in 2080 projected between 0.01–1.5. ▪ The % increase in urban land use (relative to 2000) are projected across four scenarios as 1.38% (2020s), and ranging between 3.42–4.11% (2050s), and 3.42–6.16% (2080s). *Based on a continuous trend through the projection period, as considered in the paper, the % changes (relative to 2010) are estimated between: 0.68 (2020s); 2.72–3.40% (2050s); and 2.72–5.44% (2080s).*	▪ EEA (2007) ▪ Rounsevell *et al*. (2006) ▪ Reginster and Rounsevell (2006)
Flooding		
People flooded in a 1 in 100 year (coastal and fluvial) flood event (PF100)	Coastal flooding: ▪ Additional number of people at risk of flooding (*1000/year, relative to 1995 levels): 10–11 (2000s), 10 (No SLR)–24 (A1B/95%ile) (2020s), 10–90 (2050s), and 10–425 (2080s). ▪ Additional number of people flooded (*1000/year): 14.8 (B1)–15.0 (A2) (2010), 20.1–21.3 (2030), 28.9–35.0 (2050), 204.5–776.2 (2100). ▪ Additional number of people flooded (*million/year): 0.036 (1995) and 0.78–5.55 (2080s) (i.e., 0.78 (Temp=2.5°C), 1.23 (Temp=3.9°C), 0.85 (Temp=4.1°C), 1.35 (Temp=5.4°C), and 5.55 (high SLR=88cm)). Fluvial flooding: ▪ Number of people affected (*1000/year): 150–195 (base year), 140–250 (2000s), 150–485 (2020s), 150–480 (2050s), and 140–810 (2080s). ▪ Number of people affected (*1000/year): 194.0–196.2 (control year), and 445.1–589.9 (2080s) (i.e., 468.7 (Temp=2.5°C), 513.3 (Temp=3.9°C), 445.1 (Temp=4.1°C), and 589.9 (Temp=5.4°C)). ▪ Number of people affected (*1000/year): 140–202 (control year), 165–260 (2000s), 215–405 (2020s), 160–400 (2050s), and 200–785 (2080s). ▪ Number of people affected (*1000/year): 194 (control year), and 251–396 (2080s) (i.e., 276 (Temp=2.5°C), 318 (Temp=3.9°C), 251 (Temp=4.1°C), and 396 (Temp=5.4°C)). Combined flooding: ▪ Number of people flooded (millions): 0.24–17.4 (baseline), and 14.23–20.38 (2050). *Assuming*	▪ Brown *et al*. (2011) ▪ Hinkel *et al*. (2010) ▪ Ciscar *et al*. (2009) ▪ Rojas *et al*. (2013) ▪ Feyen *et al*. (2012) ▪ Feyen & Watkiss (2011) ▪ Ciscar *et al*. (2009) ▪ Mokrech *et al*. (2015)

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continuation of the proportion, the % change (relative to baseline year, i.e., 2010) is estimated in the ranges between -21.5 and 41.6% (2080s).

▪ Number of people exposed to flooding (millions): 91.5 (2000), 92.5 (2010), 91 (2025), and 85 (2050). Assuming continuation of the trend, the % change (relative to 2010) is estimated in the range of -11.4% (2080s).

▪ As the analysis considers combined (coastal and fluvial flooding), all combinations of the three coastal and four fluvial flood impact studies listed above with comparable analysis (i.e., a total of 3 coastal x 4 fluvial x 2 (min. and max.) = 24) were considered to estimate the approximate ranges of the combined % change in 2080s (relative to 2010; assuming a continuous line/curve fitting across the projected time periods considered in each study). These resulted in the ranges between -0.4 and 40.9% (as summarised below).

Summary:
<table>
<tr><th></th><th>F1</th><th>F2</th><th>F3</th><th>F4</th></tr>
<tr><td>C1</td><td>-0.4 – 20.6</td><td>7.1 – 22.3</td><td>1.5 – 22.0</td><td>1.5 – 16.8</td></tr>
<tr><td>C2</td><td>1.3 – 12.3</td><td>8.4 – 11.6</td><td>3.0 – 13.2</td><td>2.7 – 5.6</td></tr>
<tr><td>C3</td><td>8.7 – 34.7</td><td>13.0 – 40.9</td><td>9.5 – 37.3</td><td>7.8 – 35.3</td></tr>
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<td>▪ Jongman et al. (2012)</td>
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<td>Agriculture</td>
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<td>Food production (FP)</td>
<td>
▪ Estimated change in agricultural area (as % of total European land area) by 2080s (relative to 2010): -6.4 to -10.7% (cropland) and -1.1 to -10% (grassland). Assuming similar proportional change in production (and considering the average and sum total combinations of the two types of agricultural land use, respectively), the ranges of % changes are estimated in between: (i) -3.7 and -10.3%, and (ii) -7.4% and -28.7%.

▪ Annual growth rate of the European agricultural production (as % change, between 2008 and 2025) is projected in the range between: +0.25 to +1.42% (across four scenarios); Annual growth rate of the European agricultural land use (as % change, between 2008 and 2025) is projected in the range between: +0.03 to +0.08% (across four scenarios). Assuming a continuation curve fitting of the minimum and maximum annual growth trends (across the four scenarios and between 2010 and 2025) and using both the proportions as a proxy indicator, the ranges of the total % changes by 2080s (relative to 2010) are estimated between: (i) +16.5% and +32.5%, and (ii) -2.7% and +11.4%.

▪ The % change in production growth of all agricultural food products (including primary agriculture and processed food products and livestock) (between 2007 and 2020) is projected in the ranges
</td>
<td>
▪ Rounsevell et al. (2006)

▪ Boitier et al. (2008)

▪ Nowicki et al. (2009)
</td>
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	between: +2.6 to 6.25% (across three scenarios). *Assuming a continuation of these proportional changes, the total % change by 2080s (relative to 2010) is estimated in the ranges between +15.0% and +36.3%.*	
	▪ European % change in crop yields (2080s) based on the Mean±SD projections (under four scenarios) averaged across the different regions: (i) -14.7 to +29.1%, (ii) -10.2 to +23.3%, (iii) -8.6 to +25.2%, and (iv) -3.7 to +27.4%. *These ranges are considered assuming similar proportional change in production the ranges across the scenarios.*	▪ 1Iglesias *et al*. (2012)
	▪ European average % change in crop yields (relative to the 1961–1990 period): +17% (2020s), and +3% (Temp=2.5°C), -2% (Temp=3.9°C), +3% (Temp=4.1°C), and -10% (Temp=5.4°C) (2080s). *Considering a continuous curve fitting for the study period, the European average % changes (relative to 2010) is estimated in the ranges between -13.6% and +3.4%*.	▪ Ciscar *et al*. (2011)
	▪ Aggregated % changes in average crop yields across different scenarios are projected between: -3–8% (HadCM3) and 5–7% (HadCM2). *Assuming that the developed country projections can also be applied for Europe with similar proportions, hence the average % changes ranging between +3% and +8% are considered here*.	▪ Parry *et al*. (2004)
	▪ Average % change in agricultural yields (for all production) by 2050s (relative to baseline): -7% to +29%. By 2080s, the ranges of % change are estimated between *-9.7% and +39.7%*.	▪ Audsley *et al*. (2006)
	▪ The % of total agricultural use land area is projected between -4.5% and 0% (2000–2030). *Assuming extrapolation of these changes and similar proportional change in production, the % change by 2080s (relative to 2010) is estimated between -12% and 0%*.	▪ Verburg *et al*. (2008)
Forestry		
Timber production (TP)	▪ A time series of the proportional change in annual timber production is projected (across two scenarios) ranging between: 0.2–0.28 (2020s), 0.02–0.05 (2050s), and 0.21–0.13 (2080s). *Based on the time series projections, the % changes by 2080s (relative to 2010) are estimated in the ranges between -37.6% and +17.7%*.	▪ Sohngen and Sedjo (2001)
	▪ The % change in timber production based on two scenario is projected in the range between: 5–10% (1995–2045), 2–13% (2045–2095), and 14–26% (2095–2145).	▪ Sohngen *et al*. (2001)
	▪ Projected forest (%) of land area: 37.3% (2000), 37.7% (2010), 37-8–38.4% (2020s), 36.8–40.5% (2050s), and 37.4–41.1% (2080s). In addition, the change in forest areas (as % of total European land area) by 2080s: 0.8–5.7%.	▪ Rounsevell *et al*. (2006)

	▪ The relative % change in projected future total direct timber production (relative to the 2005–2014 historic average) range between: 7.8–9.5% (2020s), 9.6–11.3% (2050s), 11.5–13.2% (2080s). ▪ % increase in forest area (between 2000 and 2020) is projected at 5%. By 2080, this is estimated approximately to increase by 18.8% (relative to 2010). *Here, % change of area is used as a proxy assuming similar proportional change*. ▪ % change in forest area projected (between 1990 and 2050): 0–3% (2050s). *The % change by 2080s (relative to 2010) is estimated between 0–3.5% (2080s). Here, % change of area is used as a proxy assuming similar proportional change*. ▪ % change in timber production: 5–15% (2020s), 20–40% (2050s), 20–60% (2080s). This provides a global context. ▪ % change in wood increment (1990 to 2080) (due to forest management) is projected, across different scenarios, to: decline by 10% and increase by 2.9–9.7%. *The overall range in the % change projection (relative to 2010) is estimated in the range between -7.8% and +7.7%*.	▪ Eurostat (2015) ▪ EEA (2010) ▪ Karjalainen *et al*. (2003) ▪ Easterling *et al*. (2007) ▪ Schroter *et al*. (2005)
Diversity		
Land use diversity (LUD)	▪ Aggregate land use change (%) trends by 2080s: <1% (urban), -11 to -6.2% (arable), -9 to -1% (grassland), +4 to +9% (biofuels), and 0 to +11% (surplus). *The % change ranges in land use diversity (base on the Shannon index) by 2080s (relative to 2010) is estimated between -30.3% and +6.8%*. ▪ The % change in aggregate land use classes (2009–2012). +0.4% (artificial land), -0.4% (cropland), +2.7% (woodland), -0.5% (shrubland), -0.4% (grassland), -0.3% (bareland), -0.1% (water), and -0.3% (wetland). *Considering extrapolation of the current trend, the % change in diversity by 2080s (relative to 2010) could be estimated at 17.5%*.	▪ Schröter *et al*. (2004; 2005) ▪ Eurostat (2011)
Water		
Water exploitation index (WEI)	▪ The ratio between water use and resource (%) is estimated for baseline year and projected for future as: 6% (1995), 6–7 (2015), and 5–7 (2032). *Assuming continuous trend of these projections, the average % change in 2080s (relative to 2010) is estimated in the ranges between +20% and +125.7%*. ▪ Historic four years average time series % of water withdrawal to total water resources ratios for the EU-28 range from 0.150 (1983-1987) to 0.132 (2008–2012) (with overall average of 0.125 for 1983–2012). *Assuming extrapolation of the historic trends (considering the full period as well as the last two decade trends), the % changes (relative to 2010) are estimated between -3.2% and +28.8%*	▪ UNEP (2004) ▪ FAO (2015)

	(2020s), -20% and +74.4% (2050s), and -46.4% and +144.0% (2080s).	
	▪ Change in water stress (measured using change in withdrawals-to-availability ratio of more than 0.4) is estimated to increase from +19% (at the baseline of 1995) to between +34% and +36% (2070s). *Using these projections, the indicative % change in 2080s (relative to 2010) is estimated in the ranges between +14.1% and +15.9%*.	▪ Henrichs *et al*. (2002)
	▪ The % change in water withdrawals by 2025 (relative to 1995 levels) is projected at: -4.3%. *This helps to compare with the socio-economic scenarios investigated, as it assumes changes only due to the effect of socio-economic change drivers (e.g., without climate change)*. *Using this projection, the indicative % change in 2080s (relative to 2010) is estimated at -10.5%*.	▪ Alcamo *et al*. (2003)
	▪ Projections of % change in water withdrawals (relative to 1995 levels) range between: 5.4–6.1% (2025), 11.6–12.9 (2055), and 7.6–14.0% (2075). *Considering extrapolation of these projections, the indicative % change in 2080s (relative to 2010) is estimated in the ranges between +8.8% and +12.9%*.	▪ Alcamo *et al*. (2007)
	▪ The current and future projected change in water stress (relative to 2005 levels) is estimated as: -0.001–0.02 (2010), 0.08–0.13 (2025), 0.15–0.28 (2045) (due to climate change) and 0.02–0.06 (2010), 0.22–0.31 (2025), 0.39–0.60 (2045) (due to both economic growth and climate change). Hence, the % change ranges (by 2080s relative to 2010) are estimated between 31.6–46.9% (climate change) and 82.7–112.5% (climate and socio-economic change). This provides a global context.	▪ Schlosser *et al*. (2014)
	▪ Projections of European average % change in water stress indicator in 2025 (relative to 1985 levels) (under three scenarios) range between: -1.9–31.0%. *Similarly, the indicative % change in 2080s (relative to 2010) is estimated in the ranges between -3.6% and +58.1%*.	▪ Vörösmarty *et al*. (2000)
Biodiversity		
Biodiversity vulnerability index (BVI)	▪ Average % loss of species by 2050s (relative to 1990): 7–58% (B1), 8–53% (B2), 8–59 (A1FI), and 8–55% (A2). *When considering the % change in 2080s (relative to 2010), the losses are estimated in the range between 8.8% and 73.7%*.	▪ Schröter *et al*. (2005)
	▪ The average % change in vulnerability (i.e., loss and gain) of species by 2080s is projected between: +44.5% and -18%, respectively.	▪ Schröter *et al*. (2004)
	▪ Projections of biodiversity vulnerability measured as % change in the number of species (by 2050s relative to 2000) range between: -0.01% to -5.4%. *By 2080s (relative to 2010), these % changes can approximately be estimated in the ranges between -0.02% and -8.1%*.	▪ Ding and Nunes (2014)

	▪ The average % of species and habitat that are negatively affected by climate change (i.e., increased vulnerability) is estimated at: +12% (species) and +19% (habitat). ▪ Average % loss of wetland habitat due to temperature change (between +2.4^{o}C and +4.4 ^{o}C by end of century) is estimated between +38.3% to +71.7%. ▪ The projected % loss of species (birds and plants) by 2050 due to climate change is estimated between 4–38% and 3–21%, respectively. *Extrapolation of these trends suggests that by 2080s (relative to 2010), the % change ranges could be estimated in the range between 6–57% and 4.5–31.5%, respectively*.	▪ EEA (2010) ▪ Hare (2005) ▪ Thomas *et al*. (2004)

C. ODAT Sensitivity Analysis: Statistical Summary of the River-Basin Regional Sensitivities

Table B0.1 (A–D): *Regional statistical summary of sensitivity of the sectoral indicators to changes in the various future climate and socio-economic drivers affecting each indicator*.
(A) Western Europe (WE):

Drivers	SECTORS (Indicators)																				
	Urban (AS)			Flooding (PF100)			Agriculture (FP)			Forest (TP)			Land use (LUD)			Water (WEI)			Biodiversity (BVI)		
	Baseline = 6.48%			*Baseline = 8.28 million*			*Baseline = 4753.6 TJ*			*Baseline = 106.47 Gt*			*Baseline = 0.911*			*Baseline = 0.189*			*Baseline = 0*		
	Mean	Range	SD	Mean	Range	SD	Mean	Range	SD	Mean	Range	SD	Mean	Range	SD	Mean	Range	SD	Mean	Range	SD
CLIMATE DRIVERS:																					
1 Temp	–	–	–	8.20	0.28	0.10	5146	613.2	205.9	62.85	71.09	23.97	0.923	0.061	0.023	0.214	0.065	0.022	0.192	0.466	0.181
2 WPrec	–	–	–	8.38	1.17	0.50	4783	441.6	189.3	90.36	73.14	29.04	0.912	0.056	0.023	0.208	0.188	0.070	0.017	0.130	0.048
3 SPrec	–	–	–	8.38	1.17	0.50	4679	1148.1	429.2	60.57	108.14	43.03	0.873	0.118	0.044	0.208	0.189	0.071	0.048	0.190	0.075
4 CO_2	–	–	–	–	–	–	5148	700.4	217.8	77.03	51.97	21.71	0.866	0.117	0.037	0.190	0.002	0.001	0.065	0.126	0.047
5 SLR	–	–	–	15.79	13.79	4.85	4586	262.0	85.2	105.49	1.57	0.62	0.901	0.027	0.010	0.189	0.000	0.000	0.002	0.006	0.002
SOCIO-ECONOMIC DRIVERS:																					
6 Population	6.61	0.43	0.18	8.34	8.53	3.18	4618	4357.5	1713.6	55.21	103.86	40.14	0.842	0.199	0.075	0.189	0.028	0.010	0.062	0.182	0.067
7 StructChange	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	0.189	0.042	0.016	–	–	–
8 Ruminant	–	–	–	–	–	–	4821	229.7	105.7	93.02	41.85	19.27	0.914	0.029	0.011	0.189	0.000	0.000	0.007	0.014	0.007
9 NonRuminant	–	–	–	–	–	–	4675	2098.1	717.9	98.39	46.10	18.64	0.912	0.087	0.031	0.189	0.000	0.000	0.008	0.029	0.011
10 GreenRed	6.51	0.05	0.02	–	–	–	4752	2.7	1.2	106.44	0.05	0.02	0.911	0.001	0.000	0.189	0.000	0.000	–	–	–
11 GDP	9.33	6.38	2.28	–	–	–	4619	570.1	182.2	92.55	25.52	7.10	0.946	0.083	0.027	0.201	0.032	0.010	0.009	0.016	0.005
12 OilPrice	–	–	–	–	–	–	5001	428.9	749.3	86.28	39.09	15.62	0.948	0.090	0.039	0.189	0.000	0.000	0.003	0.007	0.002
13 BioEnergy	–	–	–	–	–	–	5004	478.2	226.4	91.86	30.30	13.84	0.498	0.023	0.011	0.189	0.000	0.000	0.003	0.007	0.003
14 ImportFactor	–	–	–	–	–	–	3489	5014.9	1995.6	92.74	71.01	31.61	0.845	0.290	0.114	0.189	0.001	0.000	0.071	0.202	0.082
15 SetAside	–	–	–	–	–	–	4722	272.4	117.0	103.59	14.47	6.47	0.507	0.009	0.004	0.189	0.000	0.000	0.001	0.003	0.002
16 ReduceDiffuse	–	–	–	–	–	–	4813	363.9	145.8	74.63	50.04	22.47	0.894	0.049	0.021	0.190	0.002	0.001	0.005	0.005	0.002
17 ForestMgmt	–	–	–	–	–	–	4761	13.8	7.0	87.73	35.93	18.02	0.921	0.017	0.009	0.189	0.000	0.000	0.003	0.006	0.003
18 TechFactor	–	–	–	–	–	–	4765	173.9	65.8	95.80	15.59	5.74	0.881	0.046	0.016	0.189	0.001	0.000	0.008	0.011	0.004
19 TechChange	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	0.206	0.208	0.080	–	–	–
20 YieldFactor	–	–	–	–	–	–	4175	1703.9	601.5	78.70	106.62	47.39	0.871	0.202	0.067	0.196	0.043	0.016	0.062	0.120	0.042
21 IrrigEfficiency	–	–	–	–	–	–	4663	307.8	121.2	104.89	6.55	2.31	0.914	0.008	0.003	0.191	0.008	0.003	0.003	0.009	0.003
22 DevCompaction	6.50	0.07	0.04	–	–	–	4752	3.9	2.2	106.45	0.07	0.04	0.911	0.001	0.001	0.189	0.000	0.000	–	–	–
23 CoastAttract	6.48	0.01	0.00	–	–	–	4753	0.4	0.2	106.47	0.01	0.00	0.911	0.000	0.000	0.189	0.000	0.000	–	–	–
24 WaterDistriRule	–	–	–	–	–	–	4754	0.0	0.0	106.47	0.00	0.00	0.911	0.000	0.000	0.189	0.000	0.000	0.000	0.000	0.000
25 FloodProtection	–	–	–	9.13	18.27	9.17	4673	270.4	152.3	105.86	2.40	1.31	0.903	0.021	0.011	0.189	0.000	0.000	0.010	0.029	0.017

(B) Southern Europe (SE):

Drivers	SECTORS (Indicators)																				
	Urban (AS)			Flooding (PF100)			Agriculture (FP)			Forest (TP)			Land use (LUD)			Water (WEI)			Biodiversity (BVI)		
	Baseline = 3.03%			*Baseline = 3.42 million*			*Baseline = 2472.6 TJ*			*Baseline = 35.58 Gt*			*Baseline = 1.063*			*Baseline = 0.268*			*Baseline = 0*		
	Mean	**Range**	**SD**	**Mean**	**Range**	**SD**	**Mean**	**Range**	**SD**	**Mean**	**Range**	**SD**	**Mean**	**Range**	**SD**	**Mean**	**Range**	**SD**	**Mean**	**Range**	**SD**
CLIMATE DRIVERS:																					
1 Temp	–	–	–	3.37	0.08	0.03	2100	1010.6	359.3	15.49	28.54	10.20	0.996	0.223	0.083	0.374	0.139	0.048	0.285	0.566	0.201
2 WPrec	–	–	–	3.38	0.34	0.14	2528	743.5	291.2	24.03	31.08	12.68	1.056	0.060	0.023	0.342	0.494	0.186	0.009	0.185	0.072
3 SPrec	–	–	–	3.38	0.34	0.14	2693	1257.9	481.3	16.53	31.42	10.92	1.052	0.141	0.051	0.352	0.250	0.096	-0.010	0.357	0.134
4 CO_2	–	–	–	–	–	–	2102	473.1	154.1	19.94	24.95	10.73	0.975	0.219	0.083	0.251	0.043	0.017	0.069	0.140	0.048
5 SLR	–	–	–	4.75	2.40	0.78	2411	87.2	31.1	35.35	0.32	0.12	1.058	0.009	0.004	0.266	0.003	0.001	0.003	0.004	0.002
SOCIO-ECONOMIC DRIVERS:																					
6 Population	3.08	0.13	0.06	3.30	2.93	1.12	2537	1576.3	585.7	13.46	30.23	13.26	0.961	0.238	0.092	0.326	0.073	0.031	0.037	0.181	0.072
7 StructChange	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	0.267	0.054	0.020	–	–	–
8 Ruminant	–	–	–	–	–	–	2483	190.0	65.0	31.82	10.42	4.63	1.040	0.080	0.033	0.285	0.031	0.016	0.005	0.041	0.016
9 NonRuminant	–	–	–	–	–	–	2395	1102.0	370.0	32.43	16.80	6.71	1.049	0.051	0.020	0.290	0.049	0.025	0.012	0.080	0.028
10 GreenRed	3.05	0.03	0.01	–	–	–	2472	0.9	0.4	35.58	0.02	0.01	1.064	0.001	0.000	0.268	0.000	0.000	–	–	–
11 GDP	4.23	2.76	0.98	–	–	–	2688	384.1	139.1	29.63	11.07	3.47	1.070	0.013	0.004	0.425	0.306	0.101	0.007	0.016	0.005
12 OilPrice	–	–	–	–	–	–	2605	236.9	96.7	23.13	22.71	9.80	1.113	0.115	0.050	0.302	0.054	0.019	-0.010	0.020	0.009
13 BioEnergy	–	–	–	–	–	–	2514	152.6	93.2	31.72	7.67	3.53	0.588	0.008	0.004	0.296	0.049	0.025	-0.005	0.009	0.004
14 ImportFactor	–	–	–	–	–	–	1983	1883.9	749.1	31.57	20.45	9.03	0.924	0.366	0.150	0.270	0.094	0.036	0.091	0.282	0.117
15 SetAside	–	–	–	–	–	–	2472	140.5	60.3	34.58	4.23	1.89	0.592	0.004	0.002	0.274	0.029	0.011	-0.001	0.004	0.002
16 ReduceDiffuse	–	–	–	–	–	–	2469	301.5	110.0	24.71	16.10	7.03	1.054	0.014	0.006	0.313	0.040	0.016	-0.008	0.015	0.007
17 ForestMgmt	–	–	–	–	–	–	2489	31.4	15.7	28.57	13.96	6.98	1.068	0.007	0.004	0.278	0.031	0.018	0.000	0.001	0.000
18 TechFactor	–	–	–	–	–	–	2465	207.5	69.7	30.88	7.62	2.67	1.038	0.041	0.017	0.279	0.023	0.009	-0.003	0.005	0.002
19 TechChange	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	0.275	0.169	0.064	–	–	–
20 YieldFactor	–	–	–	–	–	–	2940	1951.3	766.5	23.72	35.58	14.06	0.999	0.129	0.039	0.401	0.396	0.131	0.027	0.095	0.038
21 IrrigEfficiency	–	–	–	–	–	–	2595	656.6	252.3	31.88	9.03	3.93	1.055	0.023	0.008	0.317	0.159	0.069	0.006	0.050	0.021
22 DevCompaction	3.04	0.03	0.02	–	–	–	2472	1.0	0.6	35.58	0.02	0.01	1.064	0.001	0.000	0.268	0.000	0.000	–	–	–
23 CoastAttract	3.03	0.01	0.00	–	–	–	2473	0.2	0.1	35.58	0.00	0.00	1.063	0.000	0.000	0.268	0.000	0.000	–	–	–
24 WaterDistriRule	–	–	–	–	–	–	2471	5.0	2.5	35.54	0.17	0.08	1.063	0.000	0.000	0.264	0.012	0.005	0.000	0.001	0.000
25 FloodProtection	–	–	–	2.38	3.70	2.06	2452	69.1	38.8	35.50	0.43	0.23	1.062	0.004	0.002	0.266	0.004	0.002	0.003	0.009	0.005

(C) Eastern Europe (EE):

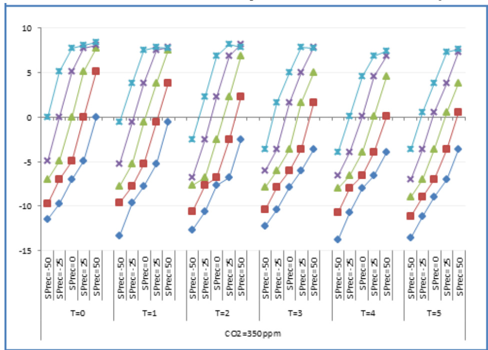
Drivers	SECTORS (Indicators)																				
	Urban (AS)			Flooding (PF100)			Agriculture (FP)			Forest (TP)			Land use (LUD)			Water (WEI)			Biodiversity (BVI)		
	Baseline = 4.08%			*Baseline = 4.65 million*			*Baseline = 2020.8 TJ*			*Baseline = 47.40 Gt*			*Baseline = 1.039*			*Baseline = 0.177*			*Baseline = 0*		
	Mean	**Range**	**SD**	**Mean**	**Range**	**SD**	**Mean**	**Range**	**SD**	**Mean**	**Range**	**SD**	**Mean**	**Range**	**SD**	**Mean**	**Range**	**SD**	**Mean**	**Range**	**SD**
CLIMATE DRIVERS:																					
1 Temp	–	–	–	4.35	0.44	0.17	2222	896.4	322.0	23.05	39.50	15.26	1.038	0.093	0.031	0.280	0.215	0.080	0.169	0.383	0.143
2 WPrec	–	–	–	4.60	1.01	0.43	1992	435.9	164.8	43.11	21.16	7.82	1.042	0.007	0.002	0.211	0.261	0.098	-0.009	0.250	0.095
3 SPrec	–	–	–	4.60	1.01	0.43	2029	351.7	139.4	36.33	69.89	26.87	0.993	0.155	0.054	0.213	0.222	0.086	0.041	0.416	0.152
4 CO_2	–	–	–	–	–	–	1970	435.2	145.4	81.25	52.36	20.36	1.042	0.067	0.021	0.177	0.015	0.005	0.024	0.080	0.028
5 SLR	–	–	–	4.91	0.46	0.15	2006	22.8	8.1	46.98	0.56	0.19	1.033	0.008	0.003	0.176	0.001	0.000	0.001	0.002	0.001
SOCIO-ECONOMIC DRIVERS:																					
6 Population	4.18	0.33	0.14	4.73	4.92	1.84	1948	2595.5	1057.3	26.02	47.47	18.94	0.907	0.380	0.135	0.197	0.043	0.017	0.092	0.282	0.101
7 StructChange	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	0.177	0.044	0.017	–	–	–
8 Ruminant	–	–	–	–	–	–	2034	272.2	91.3	42.06	16.94	7.75	1.046	0.019	0.008	0.178	0.002	0.001	0.007	0.026	0.011
9 NonRuminant	–	–	–	–	–	–	1911	1426.3	487.8	43.13	26.13	10.58	1.024	0.066	0.026	0.180	0.008	0.004	0.018	0.080	0.033
10 GreenRed	4.10	0.04	0.01	–	–	–	2020	0.8	0.3	47.39	0.02	0.01	1.039	0.001	0.000	0.177	0.000	0.000	–	–	–
11 GDP	4.46	0.89	0.31	–	–	–	1806	492.1	156.2	45.86	5.20	1.56	1.049	0.025	0.009	0.290	0.198	0.078	0.026	0.062	0.021
12 OilPrice	–	–	–	–	–	–	1961	187.8	81.4	42.60	11.16	4.12	1.035	0.036	0.013	0.182	0.015	0.006	-0.008	0.014	0.006
13 BioEnergy	–	–	–	–	–	–	2068	390.3	140.5	37.31	19.60	9.73	0.583	0.007	0.003	0.180	0.006	0.003	-0.002	0.004	0.002
14 ImportFactor	–	–	–	–	–	–	1468	2340.2	937.2	41.15	32.87	14.63	0.925	0.328	0.146	0.178	0.013	0.005	0.088	0.232	0.101
15 SetAside	–	–	–	–	–	–	2007	130.9	56.2	45.61	8.94	4.00	0.580	0.003	0.001	0.177	0.002	0.001	0.000	0.002	0.001
16 ReduceDiffuse	–	–	–	–	–	–	2036	318.9	116.8	35.06	23.55	10.39	1.031	0.039	0.015	0.187	0.025	0.010	0.005	0.019	0.008
17 ForestMgmt	–	–	–	–	–	–	2032	30.3	16.9	37.81	26.35	14.57	1.057	0.068	0.038	0.178	0.002	0.001	0.001	0.003	0.002
18 TechFactor	–	–	–	–	–	–	2352	578.8	193.3	33.01	23.69	8.07	0.991	0.136	0.052	0.178	0.002	0.001	-0.006	0.020	0.007
19 TechChange	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	0.191	0.178	0.068	–	–	–
20 YieldFactor	–	–	–	–	–	–	1824	570.0	207.3	35.19	47.73	21.30	0.940	0.260	0.090	0.238	0.289	0.102	0.071	0.129	0.049
21 IrrigEfficiency	–	–	–	–	–	–	1951	165.1	72.2	47.13	0.90	0.36	1.045	0.014	0.006	0.210	0.110	0.044	0.003	0.014	0.005
22 DevCompaction	4.09	0.03	0.02	–	–	–	2020	0.9	0.5	47.39	0.02	0.01	1.039	0.001	0.000	0.177	0.000	0.000	–	–	–
23 CoastAttract	4.08	0.01	0.00	–	–	–	2021	0.1	0.1	47.40	0.00	0.00	1.039	0.000	0.000	0.177	0.000	0.000	–	–	–
24 WaterDistriRule	–	–	–	–	–	–	2021	0.3	0.2	47.40	0.00	0.00	1.039	0.000	0.000	0.177	0.002	0.001	0.000	0.000	0.000
25 FloodProtection	–	–	–	3.24	4.44	2.53	1995	92.2	51.3	46.83	1.73	1.00	1.033	0.016	0.009	0.177	0.001	0.001	0.003	0.011	0.006

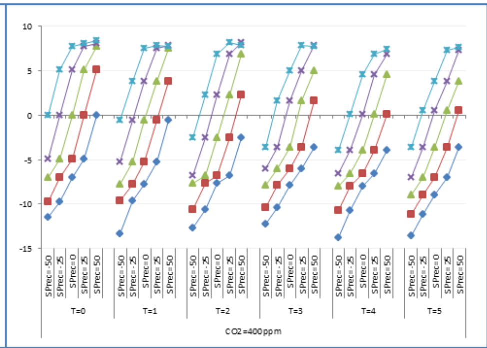
(D) Northern Europe (NE):

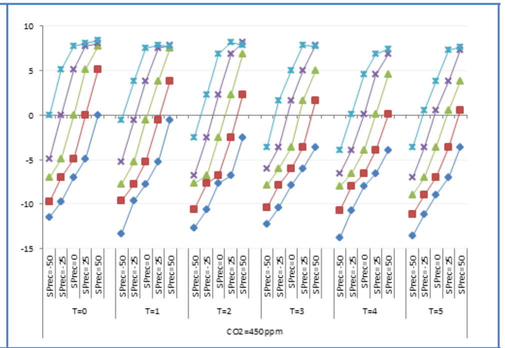
Drivers	SECTORS (Indicators)																				
	Urban (AS)			Flooding (PF100)			Agriculture (FP)			Forest (TP)			Land use (LUD)			Water (WEI)			Biodiversity (BVI)		
	Baseline = 1.22%			*Baseline = 1.06 million*			*Baseline = 596.5 TJ*			*Baseline = 72.83 Gt*			*Baseline = 0.583*			*Baseline = 0.015*			*Baseline = 0*		
	Mean	Range	SD	Mean	Range	SD	Mean	Range	SD	Mean	Range	SD	Mean	Range	SD	Mean	Range	SD	Mean	Range	SD
CLIMATE DRIVERS:																					
1 Temp	–	–	–	1.03	0.04	0.01	465	386.1	165.3	56.88	28.88	10.57	0.453	0.192	0.080	0.016	0.004	0.002	-0.102	0.199	0.072
2 WPrec	–	–	–	1.04	0.08	0.03	589	55.8	20.2	72.41	48.11	17.57	0.538	0.230	0.087	0.016	0.013	0.005	0.006	0.108	0.038
3 SPrec	–	–	–	1.04	0.08	0.03	613	220.0	79.8	62.88	106.28	38.81	0.461	0.176	0.073	0.016	0.013	0.005	0.017	0.321	0.114
4 CO_2	–	–	–	–	–	–	572	159.2	52.4	99.84	40.58	14.24	0.425	0.213	0.087	0.015	0.000	0.000	0.018	0.031	0.009
5 SLR	–	–	–	1.37	0.55	0.18	578	25.3	7.9	72.33	0.70	0.22	0.583	0.002	0.001	0.015	0.000	0.000	0.000	0.000	0.000
SOCIO-ECONOMIC DRIVERS:																					
6 Population	1.23	0.04	0.02	1.00	0.89	0.33	791	1555.3	583.1	52.73	67.26	25.55	0.486	0.334	0.152	0.014	0.005	0.002	0.031	0.073	0.033
7 StructChange	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	0.015	0.005	0.002	–	–	–
8 Ruminant	–	–	–	–	–	–	596	69.1	24.1	70.80	7.38	3.20	0.565	0.265	0.107	0.015	0.000	0.000	0.003	0.009	0.004
9 NonRuminant	–	–	–	–	–	–	577	416.3	143.7	71.70	6.49	2.63	0.516	0.222	0.109	0.015	0.000	0.000	0.006	0.018	0.009
10 GreenRed	1.22	0.01	0.00	–	–	–	596	0.4	0.2	72.83	0.01	0.00	0.583	0.000	0.000	0.015	0.000	0.000	–	–	–
11 GDP	1.85	1.38	0.50	–	–	–	707	320.8	94.3	68.36	6.24	2.23	0.486	0.162	0.067	0.015	0.001	0.000	0.002	0.023	0.006
12 OilPrice	–	–	–	–	–	–	490	221.2	106.2	72.67	0.71	0.26	0.532	0.176	0.067	0.015	0.000	0.000	0.008	0.017	0.009
13 BioEnergy	–	–	–	–	–	–	418	136.0	67.2	78.19	4.37	4.79	0.317	0.022	0.011	0.015	0.000	0.000	-0.007	0.012	0.007
14 ImportFactor	–	–	–	–	–	–	472	610.8	242.1	71.44	7.43	3.31	0.454	0.287	0.141	0.015	0.000	0.000	0.017	0.033	0.015
15 SetAside	–	–	–	–	–	–	349	23.5	10.1	79.94	2.41	1.08	0.309	0.016	0.007	0.015	0.000	0.000	-0.002	0.012	0.005
16 ReduceDiffuse	–	–	–	–	–	–	570	235.0	83.3	68.26	13.29	5.71	0.586	0.080	0.029	0.015	0.000	0.000	0.000	0.036	0.012
17 ForestMgmt	–	–	–	–	–	–	598	3.0	1.6	62.03	30.57	17.15	0.568	0.046	0.027	0.015	0.000	0.000	0.001	0.001	0.000
18 TechFactor	–	–	–	–	–	–	479	181.5	79.5	72.08	1.00	0.38	0.583	0.017	0.007	0.015	0.000	0.000	0.017	0.029	0.012
19 TechChange	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	0.015	0.018	0.007	–	–	–
20 YieldFactor	–	–	–	–	–	–	681	1005.3	365.8	59.73	72.83	27.10	0.474	0.312	0.146	0.015	0.001	0.000	0.028	0.076	0.023
21 IrrigEfficiency	–	–	–	–	–	–	560	93.8	32.6	72.50	0.55	0.24	0.582	0.023	0.007	0.015	0.000	0.000	0.004	0.010	0.004
22 DevCompaction	1.22	0.01	0.01	–	–	–	596	0.2	0.1	72.83	0.01	0.01	0.583	0.000	0.000	0.015	0.000	0.000	–	–	–
23 CoastAttract	1.22	0.00	0.00	–	–	–	596	0.0	0.0	72.83	0.00	0.00	0.583	0.000	0.000	0.015	0.000	0.000	–	–	–
24 WaterDistriRule	–	–	–	–	–	–	596	0.0	0.0	72.83	0.00	0.00	0.583	0.000	0.000	0.015	0.000	0.000	0.000	0.000	0.000
25 FloodProtection	–	–	–	0.74	1.16	0.64	591	31.2	16.3	73.10	3.65	1.84	0.580	0.010	0.005	0.015	0.000	0.000	0.001	0.002	0.001

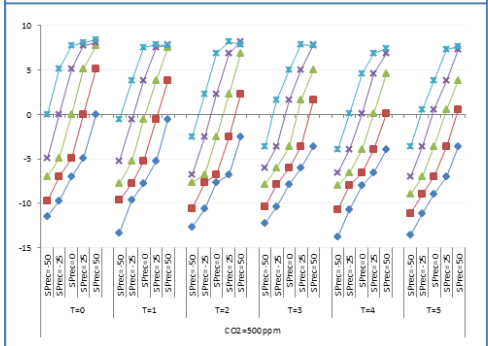
D. MDAT Scenario and Uncertainty Analysis: Results Summary

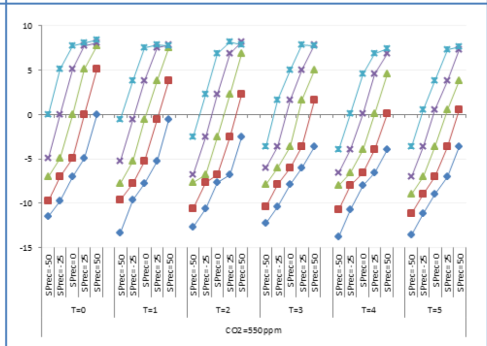
(A) FLOODING: People flooded in a 1 in 100 year flood event (PF100)

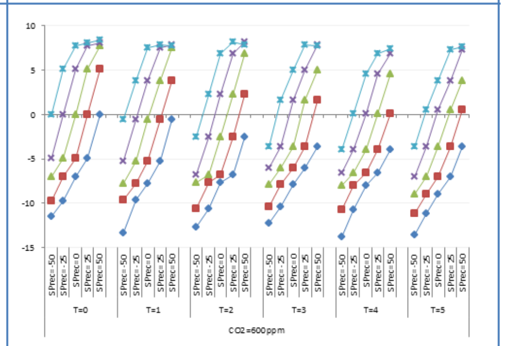


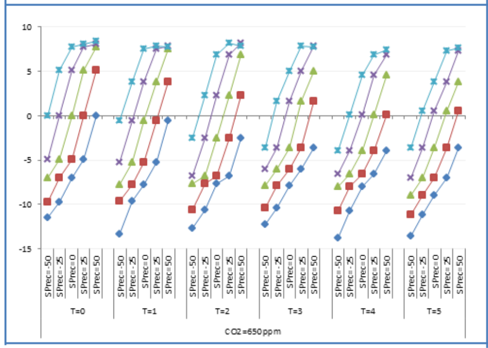


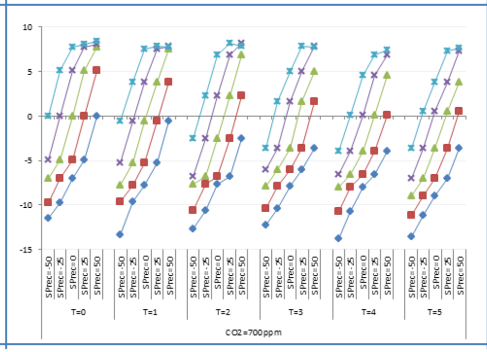










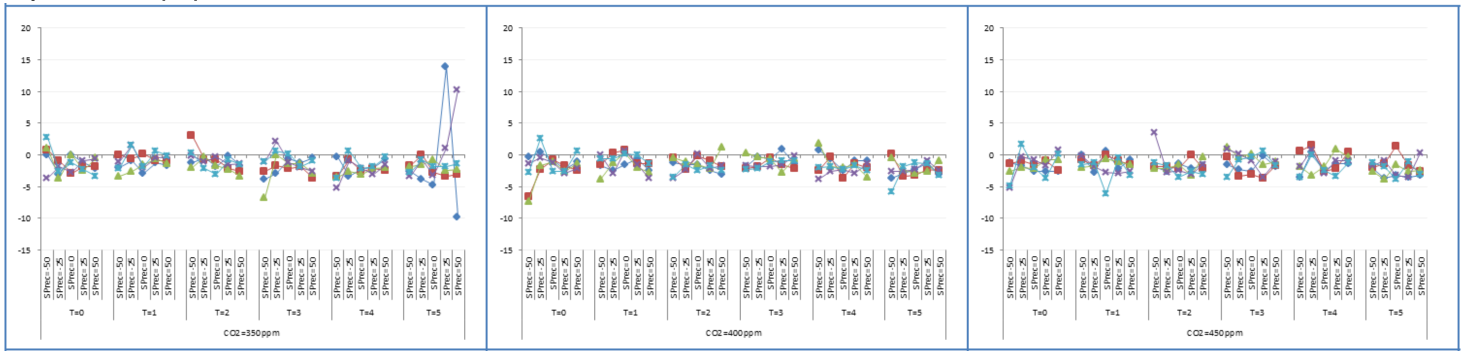


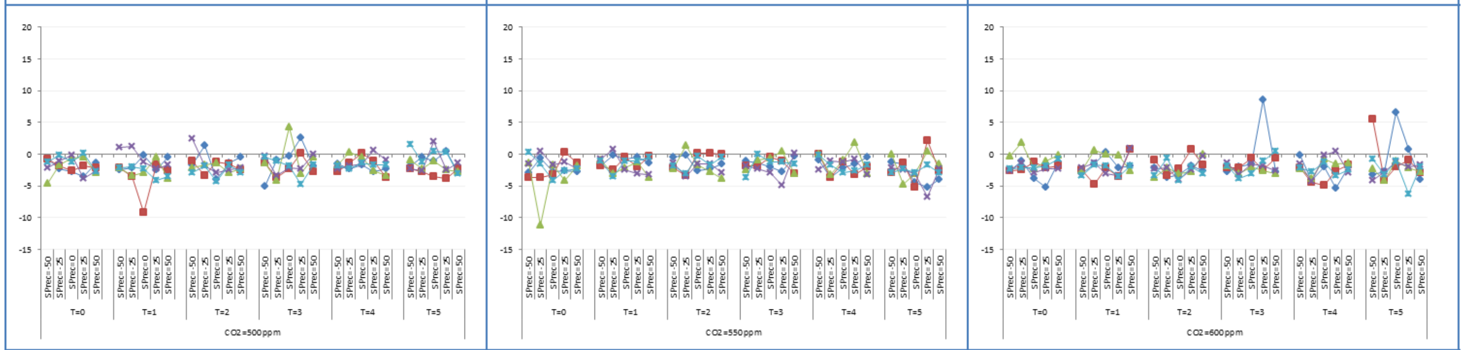
People flooded by a 1 in 100 year flood event, PF100 (EU TOTAL: % change from Baseline)

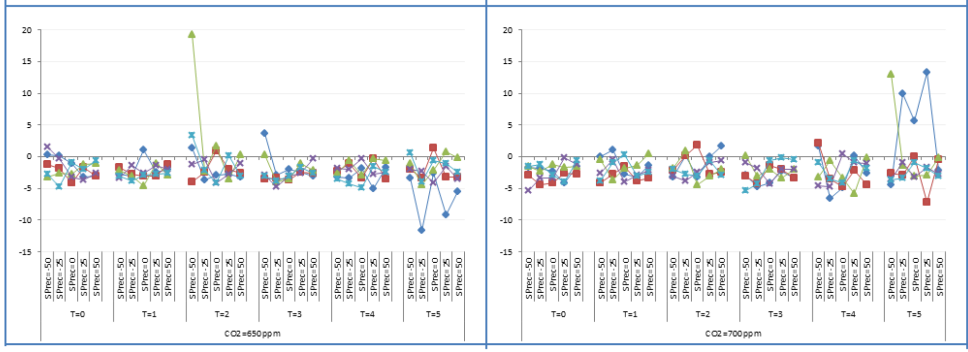
Multiple variables considered:

- *CO2 concentration (ppm)*
- *Temperature change (°C)*
- *Summer precipitation change (SPrec) (%)*
- *Winter precipitation change (WPrec) (%)*

(B) AGRICULTURE: Food production (FP)





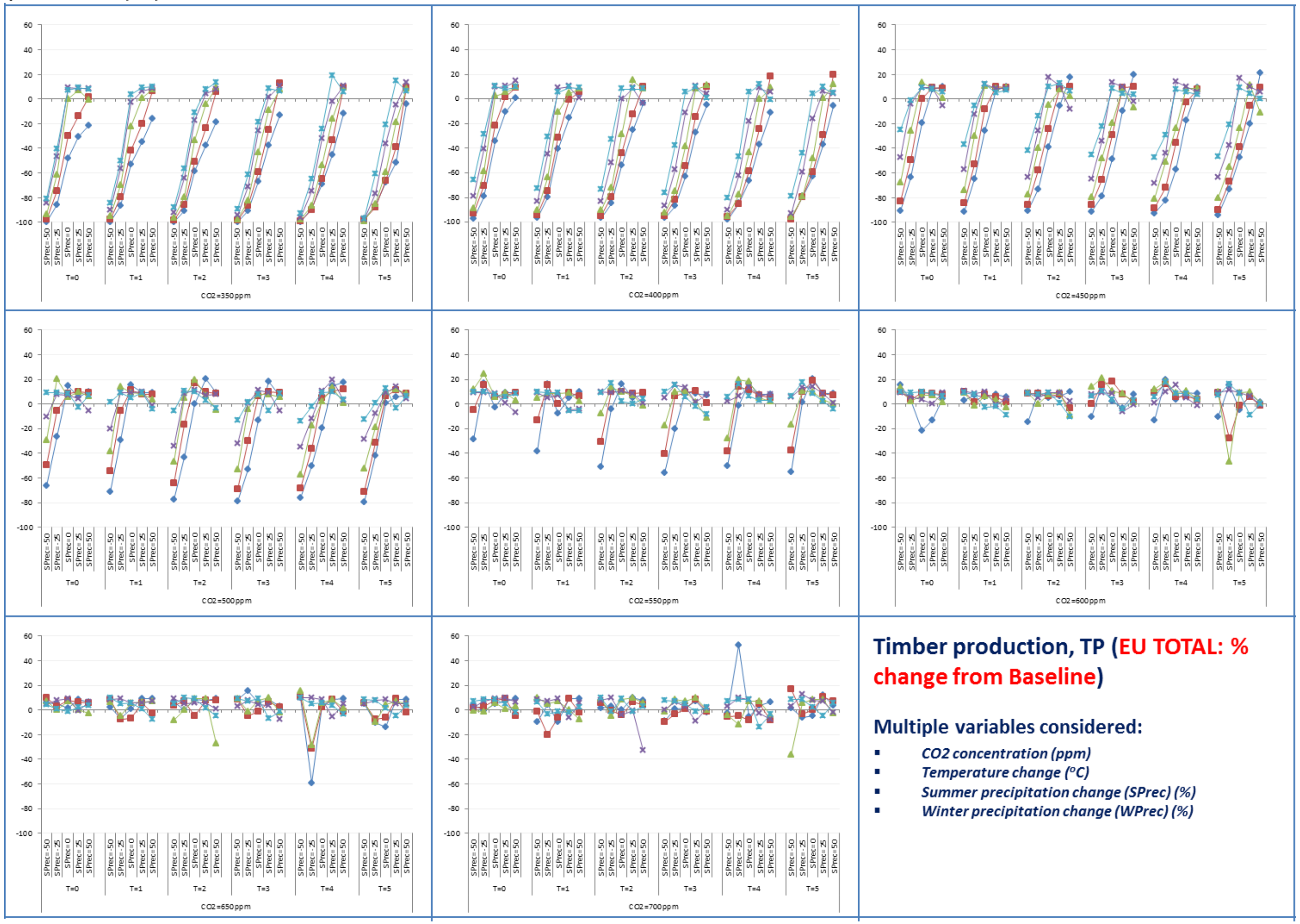


Food production, FP (EU TOTAL: % change from Baseline)

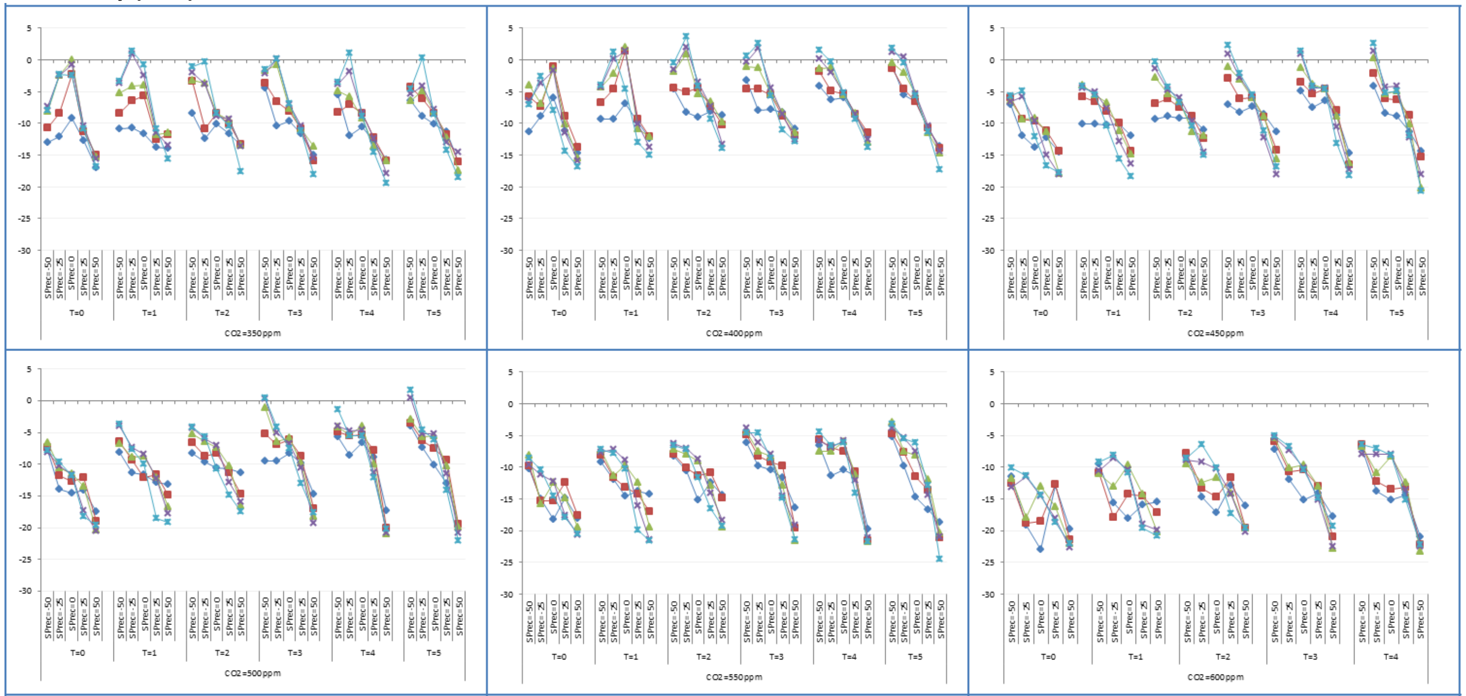
Multiple variables considered:

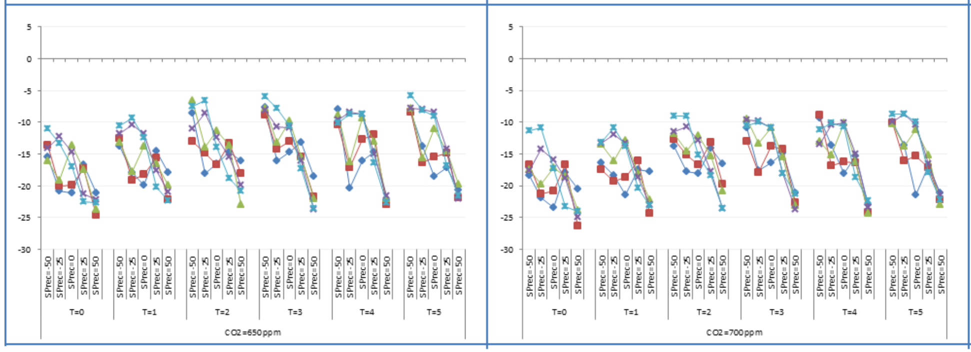
- ***CO2 concentration (ppm)***
- ***Temperature change (°C)***
- ***Summer precipitation change (SPrec) (%)***
- ***Winter precipitation change (WPrec) (%)***

(C) FORESTRY: Timber production (TP)



(D) DIVERSITY: Land use diversity (LUD)



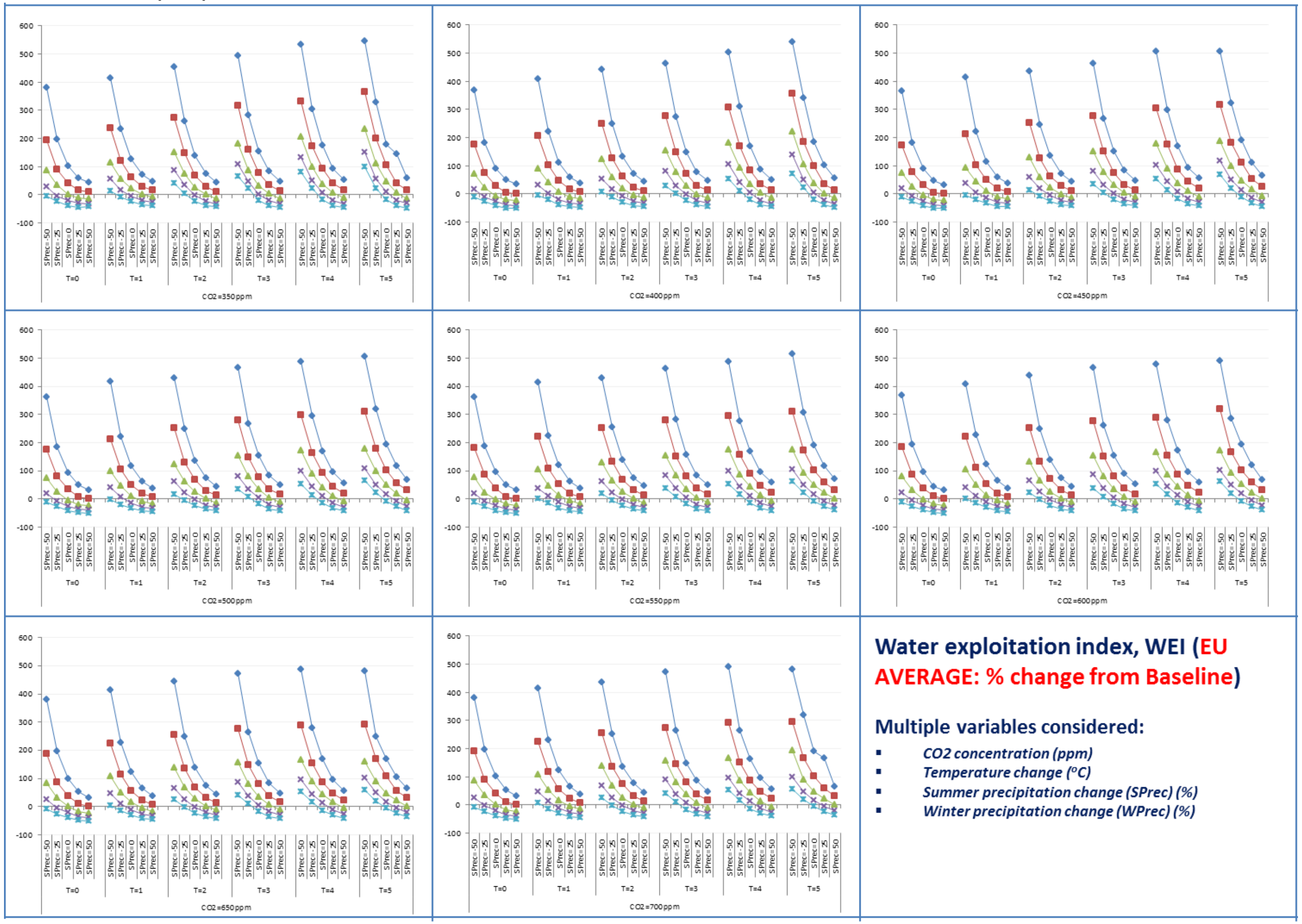


Land use diversity, LUD (EU AVERAGE: % change from Baseline)

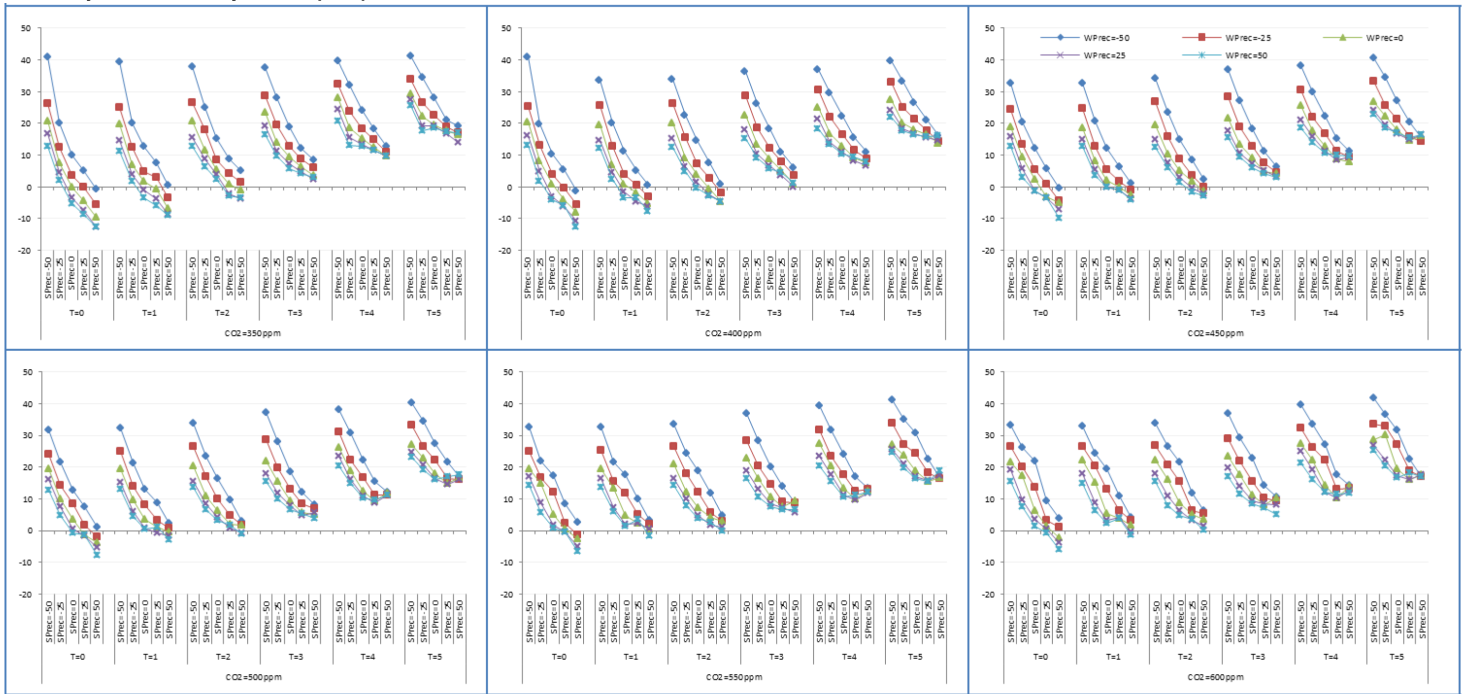
Multiple variables considered:

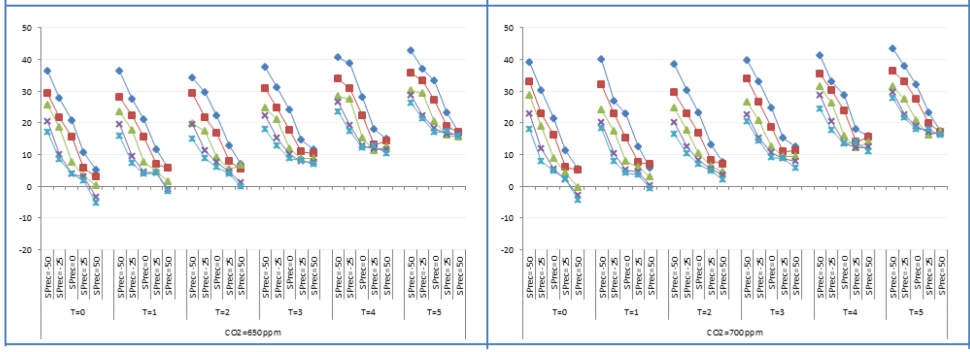
- ***CO2 concentration (ppm)***
- ***Temperature change (°C)***
- ***Summer precipitation change (SPrec) (%)***
- ***Winter precipitation change (WPrec) (%)***

(E) WATER: Water exploitation index (WEI)



(F) BIODIVERSITY: Biodiversity vulnerability index (BVI)





Biodiversity vulnerability index, BVI
(EU AVERAGE: % change from baseline)

Multiple variables considered:

- ***CO_2 concentration (ppm)***
- ***Temperature change (°C)***
- ***Summer precipitation change (SPrec) (%)***
- ***Winter precipitation change (WPrec) (%)***

E. Publications

(1) Peer-Reviewed Journal Papers

(i) *Kebede et al. (2015): Climatic Change, 128(3–4): 261–277*

Direct and indirect impacts of climate and socio-economic change in Europe: A sensitivity analysis for key land- and water-based sectors

A.S. Kebede[1], R. Dunford[2], M. Mokrech[3], E. Audsley[4], P.A. Harrison[2], I.P. Holman[4], R.J. Nicholls[1], S. Rickebusch[5,6], M.D.A. Rounsevell[6], S. Sabaté[7,8], F. Sallaba[9], A. Sanchez[7], C.-M. Savin[10], M. Trnka[11,12], F. Wimmer[13]

[1] *Faculty of Engineering and the Environment and Tyndall Centre for Climate Change Research, University of Southampton, Highfield, Southampton SO17 1BJ, United Kingdom, Tel. +44 (0) 23 8059 2134, Email: ask2g08@soton.ac.uk*
[2] *Environmental Change Institute, University of Oxford, South Parks Road, Oxford OX1 3QY, United Kingdom*
[3] *School of Science and Computer Engineering, University of Houston Clear Lake, 2700 Bay Area Blvd., Box 540, Houston, United States*
[4] *Environmental Science and Technology Department, Cranfield University, Cranfield MK43 0AL, United Kingdom*
[5] *Environmental Systems Analysis Group, Wageningen University, P.O. Box 47, 6700 AA Wageningen, The Netherlands*
[6] *School of GeoSciences, University of Edinburgh, Drummond Street, Edinburgh EH8 9XP, United Kingdom*
[7] *Centre for Ecological Research and Forestry Applications (CREAF), Universitat autonoma de Barcelona, Edifici C, Bellaterra 08193, Spain*
[8] *Ecology Department, University of Barcelona, Diagonal 643, 08028 Barcelona, Spain*
[9] *Department of Physical Geography and Ecosystem Science, University of Lund, Sölvegatan, Lund 22362, Sweden*
[10] *TIAMASG Foundation, Sfintii Voievozi 6, 010963 Bucharest, Romania*
[11] *Institute of Agrosystems and Bioclimatology, Mendel University in Brno, Zemědělská 1, Brno 61300, Czech Republic*
[12] *Global Change Research Centre AS CR v.v.i, Bìdla 986/4a, 603 00 Běrno, Czech Republic*
[13] *Center for Environmental Systems Research, University of Kassel, Kassel 34109, Germany*

Abstract

Integrated cross-sectoral impact assessments facilitate a comprehensive and policy-relevant understanding of interdependencies and associated potential synergies/conflicts/trade-offs between sectors under climate change. This paper presents an application of a regional integrated methodology, the CLIMSAVE integrated assessment platform (IAP), which incorporates important cross-sectoral linkages and feedbacks. Using the IAP, we investigate the direct and indirect implications of a wide range of climatic and socio-economic drivers on six key European sectors: agriculture, biodiversity, flooding, forest, urban, and water. The study explores impact indicators to identify: (1) those sectors and regions most sensitive to future changes, (2) the mechanisms and directions of sensitivity (direct/indirect and positive/negative), (3) the form and magnitudes of sensitivity (linear/non-linear and insignificant/weak/strong), and (4) the relative importance of the key drivers across sectors and regions. The results show that most sectors are either directly or indirectly sensitive to a large number of drivers (more than 18 out of 24 considered drivers). Over 12 drivers have indirect impacts on the forest, land use diversity, water, and biodiversity sectors, while only four drivers have indirect effects on flooding. In contrast, for the urban sector all the drivers are direct. Moreover, many of the relationships are non-linear and hence the potential for 'surprises', highlighting the importance of considering cross-sectoral interactions in future impact assessments. This holistic understanding of the complex interactions between sectors provides important information for decision-makers to formulate appropriate adaptation policies to maximise benefits and minimise unintended consequences.

Key words: *Europe, climate change*; *socio-economic change*; *cross-sectoral impacts*; *integrated assessment*; *sensitivity analysis*.

1. Introduction

Climate change is projected to impact human and natural systems worldwide. Some examples of potential impacts in Europe include: declining agricultural productivity in some regions that threatens food security (Audsley *et al.* 2006; Aydinalp and Cresser 2008); shifts in species distribution and composition of habitats/ecosystems that characterise landscapes (Green *et al.* 2003; Berry *et al*. 2006); increasing risk of flooding for people and properties and associated damages/costs (Mokrech *et al.* 2008; Hinkel *et al*. 2010); altered hydrological processes/regimes and associated effects on the availability, quality and use of water resources (EEA 2007; Bates *et al.* 2008); and adverse effects of prolonged drought on forest growth and wood production (Ciais *et al.* 2005; Lindner *et al.* 2008). These climate impacts are in addition to the continuing pressures from changing demographics, economies, technologies, lifestyles, and policies (Moss *et al*. 2010). The extent and magnitude of future impacts varies: (i) over time; (ii) across regions, ecosystems, and sectors; and (iii) with the ability of these regions, ecosystems and sectors to adapt or cope with these impacts.

Furthermore, impacts occurring in one sector or region are not likely to be confined to that particular sector or region, with a potential for cascading indirect effects with far reaching repercussions across different sectors or regions (Toth *et al*. 2003; Nicholls and Kebede 2012). However, such interdependencies are currently poorly understood (Katja *et al*. 2013). Most impact assessment studies to date have focused on sector-based analysis and often with a particular focus on the implications of climate drivers only (Holman *et al*. 2008a,b). Other drivers such as socio-economic changes have often been given little attention and when considered they are treated either independently or rigidly combined with climate scenarios. While there might be a pragmatic interest behind such approaches, they can potentially over- or under-estimate future impacts (Carter *et al*. 2007), and hence adaptation needs. However, policy-relevant impact assessments require a holistic understanding and a systematic integrated assessment of future impacts which takes account of both cross-sectoral and climate and socio-economic drivers (Holman *et al*. 2005; Harrison *et al*. 2013). Integrated assessment (IA) models provide a holistic and consistent framework that can complement existing sector-specific assessments and methods. They bring together a wide range of relevant disciplines and methods and provide a better understanding of important system inter-linkages and feedbacks to organise and deliver policy-relevant information suitable for robust decision-making (Harremoes and Turner 2001). Despite the limitations in terms of their quantitative applications, the use of IA models has grown rapidly in the past decade across a range of disciplines, scales and complexities (e.g., Kenny *et al*. 2001; Matsuoka *et al*. 2001; Holman *et al*. 2008a).

This paper presents an application of a regional IA methodology developed within the CLIMSAVE[29] project. The study considers an extensive and systematic sensitivity analysis of a wide range of climatic and socio-economic drivers where model outputs are analysed to assess sensitivities of the cross-sectoral impacts in Europe. Sensitivity analysis provides a better understanding of the relationships between input and output variables in a system or model. Such assessment is necessary to understand outputs from complex IA methods such as scenario analysis (Harrison *et al*. this volume) and uncertainty analysis (Brown *et al*. this volume). It allows the full range of possible futures to be explored to identify how sectors respond to: (i) combined climate and socio-economic drivers and (ii) impacts that cross sectoral boundaries. The paper is structured as follows: Section 2 introduces the CLIMSAVE

[29] CLimate change Integrated assessment Methodology for cross-Sectoral Adaptation and Vulnerability in Europe

approach, including how it advances existing knowledge on IA modelling applications. Section 3 provides a general description of the materials and methodology used. The results are then presented and discussed in Section 4. Finally, key messages are summarised and conclusions are drawn in Section 5.

2. The CLIMSAVE APPROACH: Cross-Sectoral Focus

The CLIMSAVE integrated assessment platform (IAP) is an interactive, exploratory web-based tool. It provides an integrated methodology that allows stakeholders to investigate cross-sectoral impacts of a range of climate and socio-economic change drivers in Europe and explore the potential for adaptation to offset or reduce any associated vulnerability. It offers broad sectoral and cross-sectoral insights which help build the capacity of decision-makers to address the complex issues surrounding climate change impacts, adaptation and vulnerability under uncertain futures (Harrison *et al*. 2013; Harrison *et al*. this volume).

The key aspects of the IAP, in terms of advancing current knowledge in IA model applications, lies in its holistic methodological framework which improves on previous studies in three important ways: (i) greater consideration of cross-sectoral linkages and interactions by integrating six different key sectors (agriculture, biodiversity, flooding, forests, urban, and water), (ii) consideration of both climatic and socio-economic factors, and (iii) multi-scale application (continental scale: Europe and regional scale: Scotland). Here, only the European scale results are considered. The development of the IAP uses meta-modelling approaches which allow integration of various sectoral meta-models to provide stakeholders with an interactive assessment tool with reasonably fast run-times (Holman *et al*. 2008a; Holman and Harrison 2012). Meta-models (also termed 'reduced-form models') are computationally simple(r) but efficient modelling techniques that emulate the performance of more complex models (Ratto *et al*. 2012). Examples of meta-model techniques used in the IAP include look-up tables, artificial neural networks, and 3D surface response diagrams. Hence, the IAP contains a series of inter-linked sectoral meta-models, a database, a wide range of climate and socio-economic scenarios, and a GIS-based user interface that captures the complex interactions and feedbacks between sectors (Figure 1).

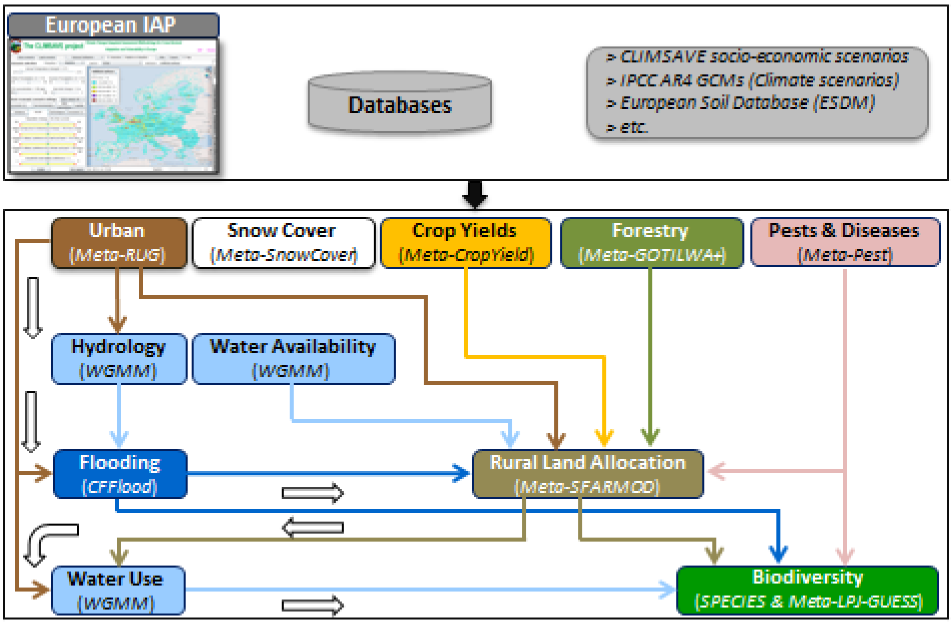


Figure 1: *Simplified schematic diagram of the various sectoral meta-model linkages and associated data flows integrated within the European CLIMSAVE IAP (Adapted from Harrison et al. 2013).*

3. Materials and Method

3.1 Scale of Analysis

The study considers five spatial extents including a Europe-wide (EU) extent and its four regions (Eastern (EE), Northern (NE), Western (WE), and Southern (WE)). The regional divisions are based on river basins classification (Figure ESM1), selected to have a consistent scale of analysis across all sectors. This is particularly relevant for the water sector, as it uses 'river basins' as its modelling spatial units, that are made up either by single large basins or clusters of smaller, neighbouring basins with similar hydro-geographic properties (Wimmer *et al*. this volume).

3.2 Selected Impact Indicators

The CLIMSAVE IAP outputs a large number of sectoral indicator variables, which were identified and prioritised based on their relevance for stakeholders and adaptation (Harrison *et al*. 2013). This analysis focusses on six key indicators (one per sector): (1) Artificial surfaces; (2) People flooded in a 1 in 100 year flood event; (3) Timber production; (4) Land use diversity; (5) Water exploitation index; and (6) Biodiversity vulnerability index (Table ESM1). The indicators are selected by experts by considering: (i) representativeness for the sector; (ii) reliability of the IAP in reproducing the observed values of the indicator; and (iii) relevance of the indicator to stakeholders.

3.3 Climate and Socio-Economic Change Drivers

A driver is defined as "any natural or human-induced factor that directly or indirectly causes a change in an ecosystem" (MEA 2005). CLIMSAVE considers two classes of underlying environmental change drivers, reflecting climatic and socio-economic change driving factors. Various definitions of drivers can be found in the literature (e.g., Anastasopoulou *et al*. 2009). In this paper, the mechanisms by which a driver affects a given sectoral indicator are classified as: (a) direct if it affects a sector as a direct IAP input to the meta-model from which the indicator was output, (b) indirect if it affects a sector by a cascading effect on another sector via the interconnected meta-model chain, and (c) combined if it affects a sector both as a direct and indirect driver (Figure ESM2). For example, sea-level rise is a direct input variable into the flood model that directly affects the number of people flooded. Conversely, food imports has an indirect impact on biodiversity through its impacts on land use patterns, which in turn affect habitat availability and thereby the biodiversity vulnerability index. Precipitation change, on the other hand, has a combined effect on biodiversity, affecting the suitability of climate space for species (direct) as well as influencing the suitability of land use for different crop types, which in turn influences available habitat (indirect).

In this paper, a wide range of future drivers of change are explored in order to understand the relationships between drivers (represented by the IAP input variables) and sectoral responses (represented by the indicators). Table 1 presents the full list of the 24 IAP inputs representing the various climatic and socio-economic drivers and the range of values selected from each driver for this analysis.

Table 1: *List of the IAP climate and socio-economic change driver variables and associated input values selected for this analysis*.

IAP DRIVER				Selected Sensitivity Values and Range			
Group/Sub-group		**Input Variables (*Units*)**	**Short Name**	Baseline	Minimum	Increment	Maximum
CLIMATE CHANGE DRIVERS:							
Climate:	1	*Annual temperature change (°C)*	Temp	0	0	1	6
	2	*Winter precipitation change (%)*	WPrec	0	-50	20	50
	3	*Summer precipitation change (%)*	SPrec	0	-50	20	50
	4	*CO_2 concentration (ppm)*	CO_2	350	350	50	700
	5	*Sea level change (m)*	SLR	0	0	0.25	2
SOCIO-ECONOMIC CHANGE DRIVERS:							
Social:	6	*Population change (%)*	Population	0	-50	20	50
	7	*Water savings due to behavioural change (%)*	StructChange	0	-50	20	50
	8	*Change in dietary preference for beef and lamb (%)*	Ruminant	0	-60	40	100
	9	*Change in dietary preference for chicken and pork (%)*	NonRuminant	0	-100	40	100
	10	*Household externalities preference (#)*	GreenRed	3	1	1	5
Economic:	11	*GDP change (%)*	GDP	0	-20	20	200
	12	*Change in oil price (%)*	OilPrice	0	0	80	400
	13	*Change in food imports (%)*	FoodImports	0	-20	20	60
Environmental	14	*Set aside (%)*	SetAside	3	0	2	8
	15	*Reducing diffuse source of pollution from irrigation (-)*	ReduceDiffuse	1	0.5	0.3	2
	16	*Forest management (-)*	ForestMgmt	Optimum	Options[a]		
Technological	17	*Change in agricultural mechanisation (%)*	TechFactor	0	0	20	100
	18	*Water savings due to technological change (%)*	TechChange	0	-75	25	75
	19	*Change in agricultural yields (%)*	YieldFactor	0	-50	25	100
	20	*Change in irrigation efficiency (%)*	IrrigEfficiency	0	-50	25	100
Policy governance:	21	*Compact vs sprawled development (-)*	DevCompaction	Medium	Options[b]		
	22	*Attractiveness of coast (-)*	CoastAttract	Medium	Options[b]		
	23	*Water demand prioritization (-)*	WaterDistriRule	Baseline	Options[c]		
	24	*Level of flood protection (-)*	FloodProtection	Minimum	Options[d]		

Options:
[a] *Forest management*: [1] Optimum, [2] Un-evenaged, [3] Even-aged (considering **5 Tree species**: (1) *Pinus sylvestris,* (2) *Pinus halepensis,* (3) *Pinus pinaster,* (4) *Quercus ilex,* & (5) *Fagus sylvatica*)
[b] *Compact vs sprawled development /Attractiveness of coast*: [1] Low, [2] Medium, [3] High
[c] *Water demand prioritization*: [1] Baseline, [2] Prioritizing food production, [3] Prioritizing environmental needs, [4] Prioritizing domestic/industrial needs
[d] *Level of flood protection*: [1] No protection, [2] Minimum, [3] Maximum

3.4 Sensitivity Analysis

According to IPCC (2007), sensitivity is defined as "the degree to which a system is affected, either adversely or beneficially, by a particular change in a climate or climate-related variable. Different systems may differ in their sensitivity to climate change, resulting in different levels of impacts". The CLIMSAVE IAP facilitates a comprehensive sensitivity analysis to investigate the response of indicators to changes in driver settings. In this paper, a "One-Driver-at-a-Time" (ODAT) approach is implemented to assess sensitivities of key European sectors to cross-sectoral impacts of both climatic and socio-economic drivers. This single-factor approach is selected as there are too many combinations of the drivers considered in the analysis as well as due to the fact that the ODAT approach provides greater understanding of the key drivers that can be used to interpret results from scenario (with change in multiple drivers) analysis (e.g., Harrison *et al*. this volume). The key stages of the sensitivity analysis are:

<u>**Step 1**</u>: *IAP sensitivity runs*

- The sensitivity runs are undertaken by modifying one input variable across the range defined in Table 1 while keeping all remaining inputs at their baseline values.
- Outputs for each driver–indicator are aggregated for Europe and the four regions.

<u>**Step 2**</u>: *Sensitivity plots and summary statistics*

- Those driver–indicator combinations with no sensitivity (zero variance) are identified and excluded from further analysis.
- The results for those drivers that affect each indicator are summarised as xy-plots for each driver–indicator combination to estimate the general trends/directions of change with changes in the driver.
- The mechanisms by which each indicator is sensitive to each driver are identified based on the CLIMSAVE variable-to-variable network (Dunford *et al*. 2014) and in consultation with the sectoral modellers.
- Key sensitivity statistics (mean, range and standard deviation) are computed for each driver–indicator combination per region. The statistics are estimated across the number of runs used to cover each driver range (Table 1).

<u>**Step 3**</u>: *Regression analysis and sensitivity thresholds*

- A standardised curve fitting analysis (using $\mathbf{I = a * D^n}$ relationship for the drivers represented in the IAP as continuous variables and $\mathbf{I = a * D}$ for the drivers represented as discrete variables) is implemented using an iterative non-linear least squares regression (e.g., Brown 2001). Where **D** (Driver) and **I** (Indicator) represent the independent and dependent variables, respectively; **a** (Strength of sensitivity) and **n** (Nature of sensitivity) represent the magnitude (rate of change as percentage) and linearity/non-linearity of sensitivity, respectively. The iteration is performed using the SOLVER macro function in Microsoft Excel©, which uses the robust and efficient Generalised Reduced Gradient (GRG) algorithm (Lasdon *et al*. 1978).
- Based on the strength of sensitivity for each driver–indicator combination: the drivers are ranked into five classes: strong increase, weak increase, insignificant change, weak decrease, and strong decrease. Insignificant change is defined as: '$-5\% \leq a \leq 5\%$'. The weak/strong thresholds are based on sectoral expert judgment.
- The nature of relationship is classified as linear for values '$0.9 \leq n \leq 1.1$', otherwise non-linear.

<u>**Step 4**</u>: *Summary of key impacts and cross-sectoral and regional comparison*

- Those sectors and regions that are most sensitive to changes in drivers are identified.
- The mechanisms (direct/indirect/combined) by which the sectoral indicators are sensitive to each driver are compared.

- The trends/directions of sensitivity (positive/negative) are examined.
- The form of sensitivity (linearity/non-linearity) is analysed.
- The relative importance of drivers, based on the qualitative ranking using the strength of sensitivity, is examined.
- Finally, which sectors gain/win and which lose and under which drivers are identified.

4. Results and Discussion

The results are summarised by focussing on five key aspects of sensitivity: (i) sectoral interdependence: the extent to which a sector is sensitive to changes in other sectors; (ii) the direction of influence of each driver: whether an increase in the driver contributes to an increase/decrease in the indicator; (iii) the nature of sensitivity: linearity/non-linearity of the relationship for each driver–indicator combination, and (iv) the level of contribution that each driver has to the sensitivity of each sectoral indicator; (v) the key drivers to which an indicator is sensitive;. Figure 2 shows a summary of the sensitivity analysis highlighting these five key aspects. Table 2 then presents the Europe-wide[30] sensitivity statistics: mean, range, and standard deviation. The results show significant differences in impacts across the sectors and regions, as discussed in detail in the following sections.

4.1 Europe-wide Sectoral Sensitivity

4.1.1 Artificial Surfaces

Future urban growth (change in artificial surfaces, AS) is driven by five of the 21 socio-economic drivers only, and all the climatic drivers have no effect (Figure 2). This is due to the urban model set-up (the variables included, Holman and Harrison 2012) and the fact that it is at the start of the meta-model chain (Figure 1), so the drivers can only have a direct effect. AS shows the highest sensitivity to GDP growth, with a Europe-wide sensitivity range greater than 3% (Table 2), followed by population growth with a range greater than 0.2%. These two variables are therefore the two principle drivers of urban growth.

The sensitivity range for the three remaining socio-economic drivers (attractiveness of coast, development compaction and household externalities preference) is less than 0.05% (Table 2). However, it is worth noting that although these drivers have less effect on the amount of AS, they play an important role in determining the spatial distribution of changes in AS. These changes in AS (both in magnitude and spatial distribution) will have important indirect implications on other sectors, as discussed below.

[30] See Table ESM2 (A)–(D) for the regional sensitivity statistics.

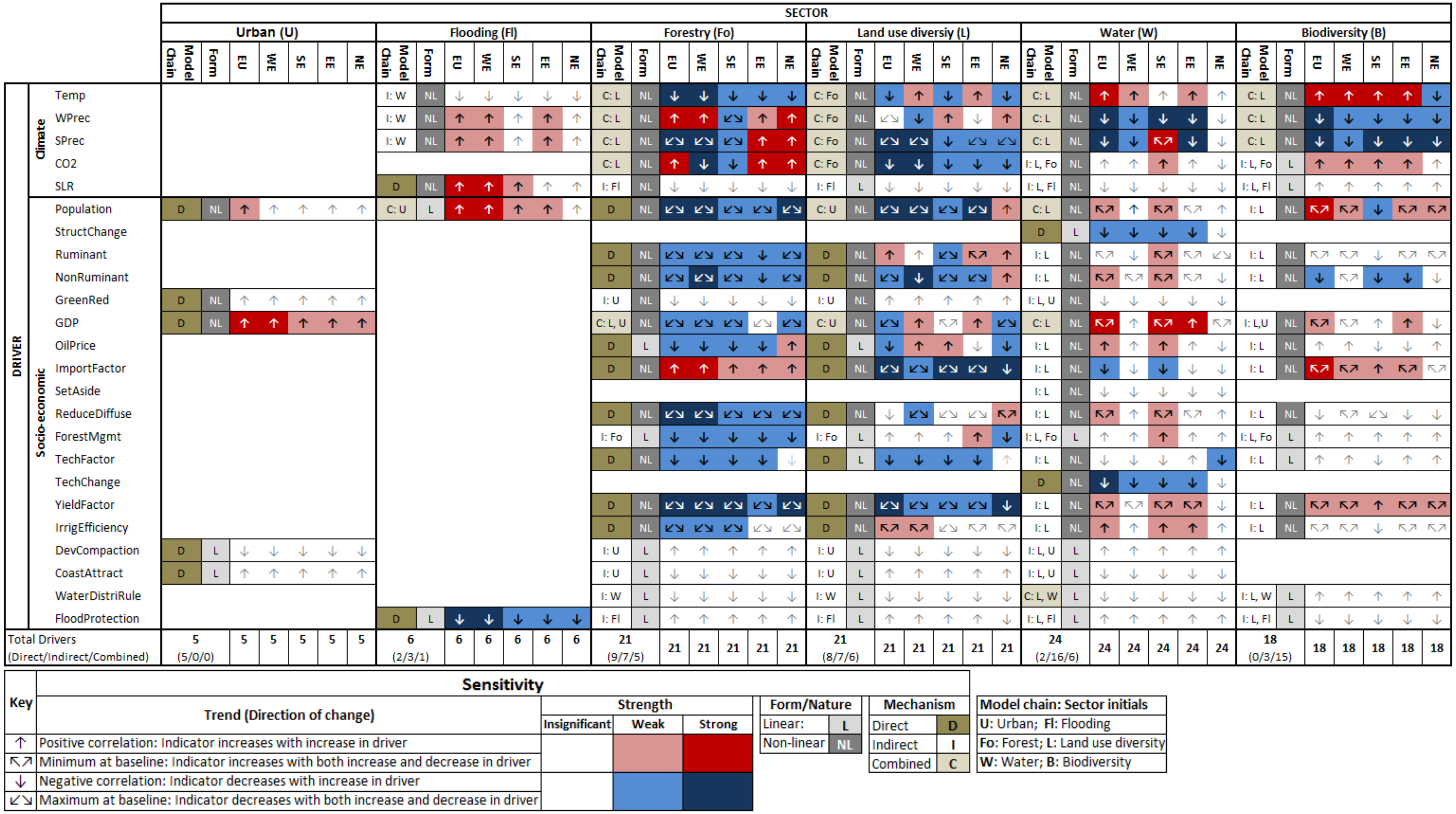


Figure 2: *Summary of the sensitivity analysis highlighting: (i) the mechanisms and directions of sensitivity (direct/indirect/combined and positive/negative); (ii) the form of sensitivity (linear/non-linear); and (iii) the 5-class ranking (strong increase, weak increase, insignificant change, weak decrease and strong decrease) of the climate and socio-economic drivers based on the strength/magnitude of sensitivity for each driver–indicator combination.*

Table 2: *A Europe-wide statistical summary of the sensitivity of the sectoral indicators to changes in the climate and socio-economic drivers affecting each sector*.

Drivers	URBAN			FLOODING			FOREST			LAND USE			WATER			BIODIVERSITY		
	Baseline = 3.67%			*Baseline=17.40 million*			*Baseline = 262.28 Gt*			*Baseline = 0.857*			*Baseline = 0.145*			*Baseline = 0*		
	Mean	**Range**	**SD**	**Mean**	**Range**	**SD**	**Mean**	**Range**	**SD**	**Mean**	**Range**	**SD**	**Mean**	**Range**	**SD**	**Mean**	**Range**	**SD**
CLIMATE DRIVERS:																		
1 Temp				16.95	0.71	0.29	158.26	159.03	58.02	0.806	0.073	0.030	0.192	0.081	0.027	0.110	0.268	0.097
2 WPrec				17.41	2.57	1.10	229.91	160.88	64.73	0.842	0.080	0.031	0.172	0.203	0.076	0.007	0.155	0.057
3 SPrec				17.41	2.57	1.10	176.32	257.77	109.63	0.796	0.125	0.049	0.174	0.144	0.057	0.026	0.304	0.111
4 CO_2							278.06	32.81	8.92	0.776	0.145	0.052	0.142	0.012	0.004	0.043	0.090	0.031
5 SLR				26.82	17.21	5.94	260.15	3.16	1.11	0.852	0.011	0.004	0.1448	0.0007	0.0003	0.002	0.003	0.001
SOCIO-ECONOMIC DRIVERS:																		
6 Population	3.74	0.23	0.09	17.37	17.27	6.47	147.43	248.73	92.38	0.761	0.856	0.093	0.160	0.024	0.009	0.053	0.163	0.059
7 StructChange													0.145	0.033	0.012			
8 Ruminant							237.70	76.43	34.72	0.849	0.105	0.041	0.149	0.006	0.003	0.005	0.010	0.005
9 NonRuminant							245.66	95.26	38.54	0.830	0.079	0.036	0.150	0.011	0.005	0.010	0.042	0.017
10 GreenRed	3.69	0.03	0.01				262.23	0.09	0.04	0.858	0.001	0.000	0.145	0.000	0.000			
11 GDP	5.03	3.05	1.09				236.40	45.56	12.93	0.840	0.034	0.014	0.200	0.101	0.036	0.010	0.016	0.005
12 OilPrice							224.68	72.48	29.09	0.861	0.031	0.012	0.153	0.013	0.005	0.000	0.005	0.002
13 ImportFactor							236.90	131.76	58.57	0.748	0.286	0.121	0.146	0.021	0.008	0.060	0.165	0.069
14 SetAside													0.145	0.002	0.001			
15 ReduceDiffuse							202.67	101.00	43.63	0.850	0.003	0.001	0.156	0.012	0.005	0.001	0.015	0.005
16 ForestMgmt							216.14	99.93	50.41	0.860	0.005	0.002	0.147	0.006	0.004	0.001	0.002	0.001
17 TechFactor							231.78	47.75	16.40	0.835	0.045	0.017	0.147	0.004	0.002	0.006	0.013	0.005
18 TechChange													0.154	0.134	0.051			
19 YieldFactor							197.34	262.28	107.08	0.779	0.135	0.048	0.184	0.142	0.048	0.046	0.083	0.031
20 IrrigEfficiency							256.40	16.66	5.89	0.857	0.009	0.003	0.161	0.053	0.022	0.004	0.011	0.004
21 DevCompaction	3.68	0.04	0.02				262.24	0.11	0.07	0.858	0.001	0.000	0.145	0.000	0.000			
22 CoastAttract	3.67	0.00	0.00				262.28	0.01	0.01	0.857	0.000	0.000	0.145	0.000	0.000			
23 WaterDistriRule							262.24	0.17	0.08	0.857	0.000	0.000	0.145	0.002	0.001	0.000	0.000	0.000
24 FloodProtection				15.49	27.58	13.89	261.29	8.21	4.19	0.853	0.010	0.005	0.145	0.001	0.001	0.004	0.013	0.008

4.1.2 People Flooded in a 1 in 100 year event

Flooding (PF100) is sensitive to six of the 24 drivers (Figure 2). Temperature and precipitation have indirect effects (via the water sector) on fluvial flooding through changes in river flood flows with a Europe-wide sensitivity range around 0.7 (temperature) and 2.6 (precipitation) million people (Table 2). Increasing temperature or decreasing precipitation results in a drier Europe (compared to the current climate) causing decreases in river flood flows, which lead to smaller fluvial floodplains, and hence less people affected. However, PF100 shows the highest sensitivity to changes in flood protection, sea level and population; with a range greater than 17 million people. Flood protection has a direct influence on PF100, with higher defences reducing impacts significantly; it shows the highest sensitivity range of 27.6 million people (the Europe-wide total being reduced by a factor of about 40, from 28.3 million people under no protection to 0.7 million people under the maximum protection). This highlights the key importance of defences and more generally adaptation, which is also consistent with other studies (e.g., Hinkel *et al*. 2013).

The direct effect of sea-level change is always positive; PF100 increases with sea-level rise due to the increase in areas at risk of coastal flooding. Under the extreme 2m sea-level rise, the Europe-wide total number of people flooded is estimated to double from the baseline estimate, reaching up to 35 million people. Conversely, the effect of population change is rather complex with a combined (direct/indirect) sensitivity. It affects both coastal and fluvial flood impacts through changes in the number of people living within floodplains (i.e., more people in floodplains potentially means more people to be flooded) and via the change in urban growth (RUG model) influencing the distribution of AS (residential/non-residential) that affects where people live, including floodplains. These sensitivities and the illustrated model behaviour help to interpret more complex changes simulated in Mokrech *et al*. (this volume) under multiple drivers of change.

4.1.3 Timber Production and Land Use Diversity

Both timber production (TP) and land use diversity (LUD) are sensitive to 21 of the 24 drivers (Figure 2). 15 of these have a Europe-wide sensitivity range greater than 15Gt (for timber), and 12 have a sensitivity range greater than 0.03 units (for diversity) (Table 2). The sensitivity of forestry is complex as it is intimately connected with the distribution of intensive agriculture (Audsley *et al*. this volume). The land use allocation model prioritises food provision. Therefore, those drivers that affect the distribution of intensive agriculture tend to have a large influence on all indicators associated with land use patterns, including TP and LUD. Hence, TP is most sensitive to indirect socio-economic factors such as agricultural yields, population, and food imports, along with the climatic drivers (temperature and precipitation) with a range greater than 130Gt. For example, an extreme decrease in crop yields results in areas which are currently forest becoming intensive agriculture to meet food provision demand, leading to a decline in TP. Similarly, an increasing population requires increased food production, which means that more land is used for agriculture leading to a decline in forest area, and hence less TP. Moreover, the climatic factors that influence timber yields often also improve crop yields leading to complex interactions in terms of overall land profitability. Greater timber yield potential also leads to less forest area being needed to produce the same levels of timber, and as such allows losses in total forest area to more profitable land uses. Hence, temperature increase is found to reduce Europe-wide forest productivity, whilst increasing precipitation leads to increased (winter) and decreased (summer) productivity. Other important indirect drivers for TP include reducing diffuse source of pollution from agriculture, forest management, and changes in oil price and dietary preferences (ruminant and non-ruminant) with a range greater than 75Gt.

LUD is also driven by complex changes in different land uses including urban, intensive arable, intensive/extensive grassland, forest, and unmanaged. As diversity is greatest in areas (grid cells) where there is a broad mix of land use, it is positively influenced by drivers that lead to new land uses becoming present in a grid cell, provided that the changes are not at the expense of a total removal of another land use. Hence, the sensitivity of LUD is influenced positively by drivers that encourage agriculture to spread more widely into new areas (e.g., change in population and dietary preferences). Conversely, it is influenced negatively by factors that: make it easier to produce more food in less area (improvements in agricultural technology or crop yields); decrease the need for crop production (increases in food imports); make it harder for agriculture to spread (hotter climates); and make other land uses more competitive (increases in CO_2 leading to increased timber yield).

4.1.4 Water Exploitation Index

The water exploitation index (WEI) is sensitive to all of the 24 drivers, which directly and/or indirectly influence the amount of water use and/or availability (Figure 2). 10 of these have a Europe-wide sensitivity range greater than 0.02 units (Table 2). Those that directly affect long-term annual water availability are precipitation and temperature. WEI shows the highest sensitivity to precipitation change: increasing precipitation leads to increasing water availability, thereby decreasing WEI. Conversely, WEI increases with rising temperature due to decreasing water availability. On the water demand side, rising temperatures lead to increasing irrigation water demand (indirect effect) and hence WEI. In addition to the climatic factors, socio-economic drivers have a direct/indirect influence on water use by affecting water demand in the domestic, manufacturing and energy (cooling) sectors, as well as irrigation water withdrawals (driven mainly by the demand for crop production and change in prices for agricultural inputs). These include crop yields, water savings due to technological change, GDP, and irrigation efficiency, all of which have a range greater than 0.05 units. The effect of changes in agricultural yields is always positive; both increasing and decreasing yields lead to increasing WEI. This is due to the fact that when yields increase the least productive agriculture areas become no longer profitable as the most productive areas are able to produce greater production of the total food demand. This has the effect of increasing the marginal value of irrigation leading to higher WEI. Similarly, a decrease in yield means that more land is used for agriculture (including in NE region) to meet existing food demand resulting in increasing irrigation water demand, and hence increasing WEI. GDP growth also leads to increasing WEI due to increasing income which increases domestic water use as more water-intensive appliances are used when people have higher incomes. Conversely, technological improvements have direct negative effect in reducing WEI through water savings due to increasing water efficiency in the domestic, manufacturing and energy sectors. Other drivers that also have some impact on WEI include: water savings due to behavioural change lowering domestic water use (↓WEI), population growth leading to higher domestic water use (↑WEI), and increasing food imports leading to declining irrigation water demand (↓WEI).

The sensitivities observed are consistent with the model structure which applies a water allocation scheme to derive actual water withdrawals in non-agricultural sectors as well as the maximum volume of water available for irrigation based on water availability and demand (Wimmer *et al*. this volume).

4.1.5 Biodiversity Vulnerability Index

Out of the 24 drivers, 18 have some impact on the biodiversity vulnerability index (BVI) (Figure 2). Of these, eight have a Europe-wide impact with a range greater than 0.02 units (Table 2). The BVI shows the highest sensitivity to climatic drivers. This is particularly true for summer precipitation and annual temperature. The influence of temperature is always positive; increasing temperature leading to increasing BVI due to decreases in the climate suitability for species, except in NE region where a warmer climate allows species from further south to become suitable leading to an increase in the number of species present. However, changes in precipitation have an inverse relationship with BVI, where increasing precipitation leads to a reduction in species' vulnerability and vice versa. Also, changes at very low levels of precipitation show more pronounced effects than those at very high levels, i.e., changes from drought to dry conditions are more beneficial for most of the species than wet conditions becoming very wet. In addition to these climatic drivers, socio-economic factors that influence the distribution of land use are also shown to have indirect impacts on BVI. These include food imports, population growth, agricultural yields, and dietary preferences. Spatial analysis of the impacts of these factors reveal that land use changes often include the full removal of arable farming from grid cells which removes habitat for arable-loving species such as the *Linnet* (*Carduelis cannabina*). Under some drivers such as agricultural yields, vulnerability increases with both increases and decreases in the driver. Increases in agricultural yields leads to productive agricultural areas producing more and those with lower productivity become less profitable and are prioritised for other uses, e.g., southern Sweden losing its arable croplands. Conversely, when agricultural yields decrease farming in NE region increases to meet demand, but declines in areas such as Lithuania where the profitability of arable land is not as great.

This combined climate and socio-economic influence on BVI is expected and reflects the SPECIES bio-climatic envelope model that underpins the index (Holman and Harrison 2012). Climate determines the boundary conditions for the species and land use determines whether or not habitats are available within the climatically suitable areas. BVI is therefore sensitive to factors that influence either of these factors.

4.2 Nature of Sensitivity and Ranking of Drivers: Cross-Sectoral and Regional Comparison

The standardised regression analysis was used to identify the form of sensitivity (linear/non-linear) and the relative importance (the 5-class raking) of the climatic and socio-economic drivers affecting each indicator. This allowed a cross-sectoral and regional comparison of impacts and the identification of which sectors lose and which gain under the key drivers (Figure 2). The results show that 18 of the 24 drivers have a non-linear effect on one or more of the sectors at the European level. Most of the non-linearities observed are related to drivers that have some indirect effect on the indicator. The urban sector is the exception, as all its drivers are direct. The indirect/combined drivers represent 46 of the 65 non-linear driver-indicator relationships. About 27% (26 out of 95) of the relationships are direct (excluding the direct effect of the combined drivers). 73% (19 of the 26 direct drivers) also appear to have non-linear effects on all sectors, except biodiversity. These results highlight the complexity and highly non-linear nature of the cross-sectoral interactions due to the cascading impacts of most climatic and socio-economic drivers across sectors. Either ignoring or having a limited understanding of these interactions could therefore lead to potential under- or over-estimation of impacts, including the possible non-linear amplifications of such interactions on the impacts (e.g., Ludwig *et al*. 2013).

The 5-class qualitative ranking of the drivers highlights the varied level of contribution of each driver to the sensitivity of each sectoral indicator in different regions (Figure 2). It also illustrates the sectoral winners (reduced impacts) and losers (increased impacts) as discussed below.

4.2.1 Cross-Sectoral Comparison of Europe-wide Impacts

At the European level, 12 of the 24 drivers have strong implications on one or more of the sectors (Figure 2). A warmer future climate generally has strong negative impacts on most sectors; biodiversity, water, and forest being the main losers, followed by land use diversity. However, increases in precipitation are positive for biodiversity and water leading to strong decreases in water stress and biodiversity vulnerability. Conversely, land use diversity loses with higher summer precipitation. Flooding also significantly increases with sea-level rise. Forestry gains strongly with increasing CO_2, which has a knock-on effect on other sectors; increasing timber yield leading to productive areas producing more of the total timber and large areas becoming abandoned, negatively affecting biodiversity and land use diversity. The implications of climate drivers on other sectors are relatively small.

When considering socio-economic drivers, while a wealthier Europe (higher GDP) is expected to experience strong urban growth, it will lead to significant stresses on water resources due to the associated additional pressures on water demand. The forest, land use diversity and biodiversity sectors also lose, albeit relatively weak in magnitude, with increasing GDP, via its influence on land use distribution such as increased labour costs leading to increased crop prices, thereby increasing irrigation profitability in some areas (e.g., the new EU countries). Similarly, increasing population has a negative effect on most sectors; the flooding, forest, land use diversity and biodiversity sectors being the major losers, followed by water. Other key socio-economic drivers include agricultural yields, food imports and dietary preferences, which have varied indirect implications across all sectors. For example, increasing food imports reduces the need for agriculture, which has a knock-on effect on other sectors, with biodiversity and land use diversity being the major losers. Conversely, the forest and water sectors win in this situation due to more land being available for forestry and declining irrigation water demand reducing the stress on water. Flooding also reduces with increased flood protection.

4.2.2 Cross-Sectoral Comparison of Regional Impacts

Figure 2 shows that 5 to 12 of the 24 drivers have strong regional implications on one or more of the sectors. A warmer climate has significant regional negative impacts on the forest and biodiversity sectors; forest losing in all regions (particularly strongly in WE), and biodiversity also losing significantly in WE/SE/EE regions. This is followed by the water sector, also losing in WE/EE regions due to declining water availability and increasing demand for irrigation. Higher temperatures also have varied regional effects on land use diversity; losing in SE/NE regions and gaining in WE/EE regions (but with a weak magnitude). However, forestry gains strongly in EE/NE regions with increasing CO_2, due to relatively higher profitability when compared with WE/SE regions. In contrast, biodiversity loses in WE/SE/EE regions with higher CO_2. In terms of precipitation, the biodiversity and water sectors are the winners. For water, increasing (both summer and winter) precipitation leads to a strong decrease in WEI, particularly in SE/EE regions followed by WE region. For biodiversity, summer precipitation is found to be more important in terms of vulnerability than winter precipitation, particularly in SE/EE/NE regions. In contrast, forest shows significant regional variation with precipitation change, which most, if not all, of the time is due to associated indirect implications on agricultural land use change. For example, forest strongly gains with increasing winter precipitation, but strongly loses with increasing summer precipitation in WE region. This is due to lower relative profitability in WE region than particularly in the NE/EE regions, where increases in precipitation always leads to increasing timber production. Flooding also loses, particularly in WE/EE regions (although relatively weak in strength).

In terms of the socio-economic drivers, those identified with Europe-wide relevance also have important regional implications on each sector. These include population, GDP, agricultural yields, food imports and dietary preferences. In addition, forest management, reducing pollution from irrigation and irrigation efficiency have notable implications. For example, the forest sector consistently loses in all regions with changes in agricultural yields due to changes in the relative profitability of the forest and agriculture sectors. Similarly, biodiversity (in all regions) and water (in SE/EE regions) also lose, again related to changes in irrigation water demand (stress on water) and changes in arable farming (effect on biodiversity). Conversely, increasing food imports has positive implications on forest (increasing TP in all regions, especially in WE region), water (especially in SE region) and biodiversity (in all regions).

5. Conclusion

This study presented an application of a Europe-wide integrated assessment tool (the CLIMSAVE IAP) based on an extensive and systematic sensitivity analysis considering a wide range of climatic and socio-economic drivers and key sectoral impact indicators. The focus of the analysis was to investigate how changes in individual drivers affect European landscape change dynamics, considering the implications of important cross-sectoral linkages and interactions and the associated direct and indirect sensitivities of impacts. The study allowed a better understanding of the complex relationships between the input driver variables and output parameters within the IAP, and helps to track if and how the effects of one driver on a sector are transferred and felt by other sectors. It also helps identify the relative importance of the drivers to each sector. The identification of drivers of change that are particularly important for different sectors or cross-sectoral interactions is crucial for a better understanding of the effects of combined climatic and socio-economic drivers that represent possible future scenarios. Such knowledge is essential to provide broad insights into the potential conflicts and trade-offs between sectors, which is important information for decision-makers who need to prioritise adaptation responses and resources to effectively reduce current impacts and address the potential effects of future changes.

The results demonstrated the overwhelming importance of considering the implications of cross-sectoral linkages/feedbacks in impact assessments. However, it is worth noting that these results do not account for non-linearities and impacts associated with changes in multiple drivers, as some scenario combinations could have much higher impacts than those presented here. Nonetheless, it provides important sectoral and cross-sectoral insights on the effects of individual drivers/stresses and helps identify the relative importance of drivers across sectors and regions. This provides a better understanding of the combined effects of different climate and socio-economic drivers (as represented by scenarios, e.g., Dubrovsky *et al*. this volume; Kok *et al*. this volume) on each sector and the associated complex cross-sectoral interactions. Building on this analysis, Harrison *et al*. (this volume) investigated the cross-sectoral implications of wide ranges of climatic and socio-economic scenario futures, which accounts for a combination of multiple driver changes. As such, these analyses provide important information to understand the potential benefits and conflicts of different adaptation measures across sectors (e.g., Berry *et al*., this volume).

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An integrated approach for assessing flood impacts due to future climate and socio-economic conditions and the scope of adaptation in Europe

M. Mokrech[1], **A.S. Kebede**[2], R.J. Nicholls[2], F. Wimmer[3], L. Feyen[4]

[1] *School of Science and Computer Engineering, University of Houston Clear Lake, 2700 Bay Area Blvd., Box 540, Houston, Texas 77058, United States. Tel. +1 (281) 283-3960, Email: mokrech@uhcl.edu*
[2] *Faculty of Engineering and the Environment, University of Southampton, Highfield, Southampton SO17 1BJ, United Kingdom*
[3] *Center for Environmental Systems Research, University of Kassel, Germany*
[4] *Joint Research Centre, Institute for Environment and Sustainability, Ispra, Italy*

Abstract

An integrated methodology for assessing coastal and fluvial flood impacts due to cross-sectoral effects of current and future climate and socio-economic conditions is presented. The change in flood frequency due to changes in river flows and relative sea level are used to determine the extent and water depth of flood risk zones. The flood damages are estimated using an approach that accounts for flood water extent and depth, urban area, population density and Gross Domestic Product. The cross-sectoral implications and benefits of a number of adaptation measures including flood protection upgrades, realignment of flood defences, resilience measures, and mixed responses for reducing flood risks are assessed. Under current conditions almost 6% of European population are estimated to live in 100 year flood risk areas. Estimated flood protection based on published data and land use types show the effectiveness of protection measures as the number of people flooded can be reduced by 39% – 96% for the 100 year event. The impacts under four pre-defined socio-economic, climate change and sea-level rise scenarios show that future climate and socio-economic conditions may increase flood impacts especially due to sea-level rise. Although exploratory analyses of increased fluvial flow demonstrated significant increase in impacts, the four pre-defined scenarios demonstrate fewer impacts caused by fluvial flooding especially in the southern and western regions of Europe. Future flood impacts of extreme scenarios can only be reduced to current levels by major adaptation measures such as upgrading flood protection by 500% or more from baseline levels.

Keywords: climate change, flood impact, integrated impact assessment, sea-level rise, climate change adaptation, wetlands

1. Introduction

Floods have significant socio-economic impacts. According to the European Environment Agency, flood events in Europe between 1998 and 2009 have caused 1126 deaths and at least €52 billion in insured economic losses. Protecting people and economic assets require a comprehensive assessment of flood impacts that analyses the cross-sectoral implications in order to design adaptation strategies that are effective in reducing flood impacts. Few studies have investigated both coastal and fluvial flood impacts. Jongman et al. 2012 have developed global methods with both spatial and temporal dynamics that looks at climate as well as socio-economic changes. They acknowledged the significant difference produced by the used models and attributed this to the inherent characteristics of models and recommended further research on the modeling of inundation characteristics and flood protection standards. The DINAS-COAST project has developed the DIVA integrated model of coastal systems for assessing biophysical and socio-economic impacts of sea-level rise and socio-economic development as well as adaptation options. The model is used by Hinkel et al (2010) to investigate the flooding impacts and adaptation in the European Union due to sea-level rise and storm surges for the A2 and B1 IPPC SRES scenarios by 2100. The analysis indicates that the differences in impacts between A2 and B2 scenarios are mainly due to socio-economic pressures (i.e. population and GDP) during the first half of the 21st century as coastal impacts are not sensitive to climate mitigation. In the second half of the century, the consequences of sea-level rise become significant. The investigation has shown substantial reduction in flood impacts due to adaptation of raising dike heights and beach nourishment. Richards and Nicholls (2009) also investigated the effects of climate change in Europe in the PESETA project across a range of scenarios using the DIVA model. They concluded that without adaptation significant impacts and therefore damages are apparent – an exploratory analysis of adaptation suggests significant benefits of coastal protection and more generally a widespread adaptation to sustain human coastal activities would be prudent.

The above studies have investigated a number of predefined scenarios where changes in the climate and socio-economic conditions will require a major investment in order to account the cross-sectoral effects that may influence flood impacts and to analyze relevant adaptation options. Holman et al 2008 have suggested integrated assessment methodologies to address this limitation; where the concept of meta-modelling can be used to establish the links between the various sectors involved. They have developed the Regional Impact Simulator that uses the DPSIR framework to allow the links and interactions between meta-models. Mokrech et al (2008) and Richards et al (2008) have developed the flood meta-model for assessing the socio-economic and environmental impacts of future climate and socio-economic conditions for East Anglia and North West England, UK.

This paper presents the **C**oastal **F**luvial **Flood** model (**CFFlood**) that is implemented in the Integrated Assessment Platform (IAP) of the CLIMSAVE project (Harrison et al. 2012) to provide estimates of the socio-economic impacts of current and future flooding that are attributed to climate change and sea-level rise in Europe's coastal and fluvial floodplains. The paper explores the results associated with some predefined scenario combinations as well as exploratory scenarios to identify trends of flood impacts. The CFFlood model is developed to provide modelling techniques similar to the flood meta-model implemented in the Regional Impact Simulator; see Mokrech et al 2008.. The CFFlood model explores both coastal flooding due to storm surge and relative sea-level rise and fluvial flooding due to change in peak flows in rivers for the 2020s and 2050s time slices in combination with changes in future socio-economic conditions. The model estimates the area at risk of flooding, people at flood risk, people affected and economic damages caused by flooding within 10' x 10' grid. The model explores the impact of a range of adaptive options that are designed to reduce impacts such as upgrading flood defence, managed realignment and flood resilience measures. The CCFlood model is developed around the integrated assessment framework known as 'Drivers-Pressure-State-Impact-Response' (DSPIR) (see Holman et al 2005a,b; Rapport and Friend 1979) in order to establish links between the various models as well as to build consistent structure for the modelling elements.

The next sections will introduce the datasets used in the CFFlood model and methodologies implemented including coastal and fluvial sub-models, flood damage estimation method, future climate and socio-economic scenarios and a range of designed adaptation options. A selected set of results will be presented to explore socio-economic flood impacts as well as cross-sectoral effects on flood impacts. The result section will also examine the benefit of adaptation measures in reducing flood impacts. Finally, key findings of this study are presented.

2. Datasets

The data inputs into the CFFlood model are acquired from readily available datasets (see key datasets in S1, supplementary material). They are mainly European scale datasets such as the CORINE land cover, while others are at a global scale such as the enhanced SRTM global topographical dataset. These datasets are pre-processed to be used by the CFFlood model in a dynamic way based on scenario conditions selected by the CLIMSAVE IAP user.

2.1 Topographic Dataset

The SRTM data at 3 arc second (i.e. almost 90 m) spatial resolution and the GTOPO30 data at 30 arc second (i.e. almost 1 km) spatial resolution have been processed to produce a DTM with full European coverage. The DTM is resampled at 200m spatial resolution and then classified into bands at 0.25 m elevation intervals along the coastline, covering the maximum range of combined sea-level rise, land subsidence and the extreme storm surge of a 1000 year event. This data set is then gridded at the 10' spatial resolution to create a look up table that allow fast data retrieval.

2.2 Indicative Flood Protection Data for Europe

Datasets on existing flood protection levels for coastal and river areas at the European level are unavailable. Hence, an indicative flood protection dataset at the European level is constructed following the UK DEFRA methodology (MAFF, 1999), where Standard of Protection (SoP) estimates of coastal and fluvial flood defences are determined based on land use/cover classes. Table 1 shows the minimum and maximum indicative standards of protection for six land use categories in fluvial and coastal flood zones for the CORINE land use/cover dataset. The resulting dataset is being revised using published data on flood protection in individual regions/nations including Belgium, the Netherlands, Northern Germany and London. For example, the Netherlands' extensive coastal defence system that provides protection up to the 1 in 10,000 year flood event and the Thames Barrier that provides London and its environs with protection against a 1 in 1000 year flood event have been included. This method provides a consistent approach for establishing a European dataset on flood protection for exploratory purposes

Table 1: *Indicative standards of protection and land use (from CORINE), (following MAFF, 1999).*

Land use band	Description	Land Use (CORINE classes – third level)	Indicative standard of protection (SOP)	
			Fluvial	Coastal
			Return period (years)	Return period (years)
A	Intensively developed urban areas.	111	50-200	100-300
B	Less intensive urban areas with some high grade agricultural land and/or environmental assets.	112, 121, 122, 123, 124, 131, 141, 142, 211, 212, 213,221, 222, 223	25-100	50-200
C	Large areas of high-grade agricultural land and/or environmental assets with some properties.	132, 133	5-50	10-100
D	Mixed agricultural land with occasional properties at risk of flooding.	241, 242, 243, 244,	1.25-10	2.5-20
E	Low-grade agricultural land (often grass) or seasonally occupied properties at risk.	31, 311, 312, 313, 321, 322, 323, 324, 333	0-2.5	0-5
F		All other classes	0	0

3. Methodology

The CFFlood model is a 2-dimensional model that consists of three main sub-model components: (1) Coastal flood, (2) Fluvial flood and (3) Habitat change/loss. Figure 1 shows the main modelling steps with data inputs and outputs at the baseline year as well as at 2020s and

2050s time slices. It also shows the models that interact with the flood model including the urban model (i.e. the RUG model) and the water gap meta-model. The above three components of the CFFlood model are coupled and integrated to a range of plausible adaptation measures that allow the analysis of plausible responses for reducing the negative impacts of future conditions. The modelling is nested at multiple spatial scales, where the input data is resampled from high resolution data sets (e.g. 100 m resolution CORINE land use data and 100 m fluvial flood maps, see electronic supplement) and the results are communicated to the IAP at 10' resolution. Due to the interdisciplinary nature of the project, the spatial resolution at the IAP level is selected at 10' grid and it requires all involved models to communicate their results at this resolution. This is not an ideal situation for modelling coastal flood impacts as the grids mostly have heterogeneous physical and social characteristics such as topography, geomorphology, landuse and population density. This restricted the use of the common segmentation technique which can produce more homogeneous segments at different lengths. On the other hand, modelling at a high spatial resolution (e.g. 500 m) and then aggregating to the IAP's grid size is also seen to be impractical due to the very long run time required for the continental scale of Europe. Thus, a pragmatic solution of using highly processed GIS data as look up tables with the above listed sub-models is seen to be the best option to produce a dynamic model that has reasonably fast runs required by the IAP. The following sections present the CFFlood model.

3.1 Coastal Flood Sub-Model

The framework of the coastal flood component (see S4, supplementary material) illustrates the main steps implemented for assessing the impacts of coastal flooding. The method uses the estimated Standard of Protection (SoP) parameter for analyzing the change in flood risk due to the effect of relative sea-level rise on extreme sea levels. It assumes that SoP decreases and flood frequency increases with a rise of extreme sea level (Mokrech *et al.*, 2008): baseline extreme sea levels are produced by a combination of astronomical tides and meteorologically-induced storm surges, and future sea levels are increased by sea-level rise. The flood risk zones are identified by analyzing the topography against the regional extreme sea levels, based on present-day extreme sea levels and relative sea-level rise scenarios, as appropriate. The flood risk zones were validated locally and regionally in selected locations (e.g. Portsmouth and East Anglia, UK); they provided fairly good agreements. Consequently the area at risk of flooding is calculated and an estimate of the people living in the flood risk zones is calculated using localized population density. A comparison between the extreme water levels and the estimated SoP determines the actual extent of flooding within these flood risk zones. Hence, the number of people who experience flooding is determined (based on the population within the flooded areas). Considering the meta-modeling approach of this work, the main limitation is that it doesn't account to other marine flood mechanisms such as wave overtopping.

3.2 Fluvial Flood Sub-Model

The fluvial flood component follows a similar approach to the coastal flood component (see S5, supplementary material). It uses flood maps for the rivers in Europe that are produced and validated using LISFLOOD simulations at 100 m resolution (Feyen *et al.*, 2011). These simulations provide flood maps for fluvial catchments (both extent and water depth) with return periods of 2, 5, 10, 20, 50, 100, 250 and 500 years, assuming no flood defences. These maps have been used as indicative maps of the flood risk zones in the CLIMSAVE project. The fluvial flood model is implemented as illustrated in Figure 3 to estimate the outputs of land area in flood hazard zones, people living in flood hazard zones, people affected and flood damages. The flood maps are analysed in conjunction with the CORINE land use data and the results are gridded at the 10‟ resolution. The estimated SoP parameter is used to analyse the change in flood risk due to changing run-off values (Mokrech *et al.*, 2008). The changes in the peak river flow are derived from the WaterGAP meta-model (WGMM).

WGMM emulates the performance of the WaterGAP3 model (Alcamo et al. 2003; Döll et al. 2003; Verzano 2009; Flörke et al. 2013) on hydrology and water use (Wimmer et al. this volume). To reduce model runtime and input data requirements, the spatial resolution of WaterGAP3 (5 x 5 arc minute) has been aggregated to 92 European river basins greater than 10,000 km². Each river basin represents either a large natural river catchment or a cluster of several smaller catchments with similar hydro-geographic conditions.

Model representation of climate change impacts on peak river flow (next to other hydrological parameters irrelevant to this study), represented by the median of annual maximum river discharge (Qmed), is realized by response surfaces specific to river basins relating changes in Q_{med} to simultaneous changes in temperature and precipitation. Response surfaces were derived from results on Q_{med} from pre-run WaterGAP3 simulations (30-year long-term statistics) with systematically modified baseline climate inputs. Modifications in temperature ([0,0.5,...,6°C]) and precipitation ([-50,-45,...,+50%]) were applied to spatio-temporal patterns in the climate dataset for the period 1971-2000 (Mitchell and Jones 2005).

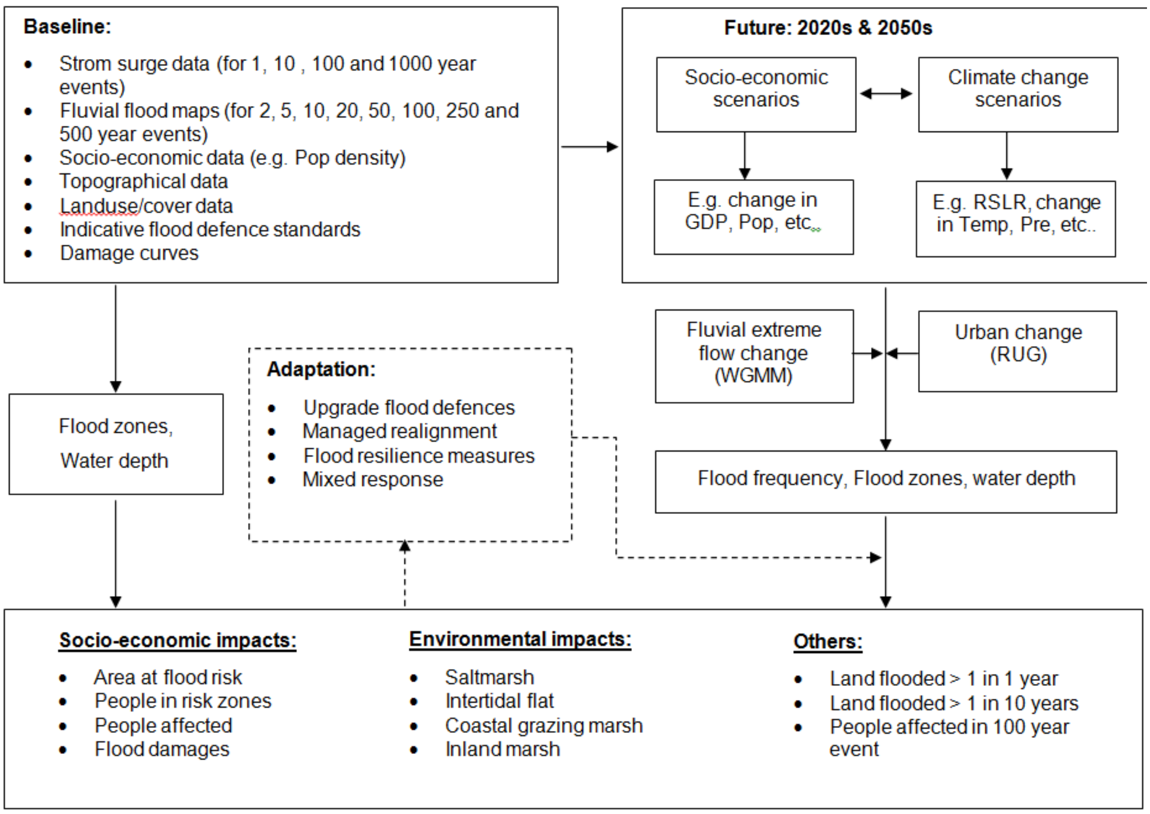


Figure 1: *Overview of the main steps, inputs and outputs of the CFFLOOD meta-model.*

When WGMM is run with scenario input data of gridded mean annual air temperature and mean annual precipitation, it first computes the relative change in temperature and precipitation compared to the baseline in each river basin. In a second step, scenario Q_{med} is interpolated by inverse distance weighting of Q_{med} at the four neighbouring grid points in the response surface. Finally, the relative change in Q_{med} compared to the baseline value is computed and passed to CFFLOOD as an estimate of changes in peak river discharge.

3.3 Structure and Content Damage

Both structural and content damages are calculated for residential and non-residential properties based on estimating flood water depth and following the broad assessment methodology of Linham *et al.* (2010). The method uses the notion that the value of physical losses from a flood is no more than the value of the assets exposed to this risk. For developed economies as is the case for Europe, the net capital asset is approximated to be 3 times the

GDP. The proportions of structural assets are considered at 36% and 42% for residential and non-residential properties respectively. Only a proportion of those assets located in a risk area are considered being exposed to flooding, as in densely populated urban areas a significant proportion of buildings are multi-story and hence a large part of the assets are above any conceivable flood level. Hence, classes of population density were used to determine the proportions of assets at risk of flooding. Then, the Dutch Depth-Damage curve is used to estimate total losses from flooding. Figure 2 shows the steps taken to calculate flood damages.

3.4 Scenarios

3.4.1 Climate and Sea-level Rise Scenarios

Climate change scenarios in CLIMSAVE were constructed following the methodology presented by Dubrovsky et al. this volume, where specific futures, emission scenarios and climate sensitivity are determined as products of changes in global mean temperature and standardized scenarios that are consistent with the AR4 of IPCC (2007). The CLIMSAVE IAP allows users to select emission scenario (i.e. A1, A2, B1 or B2), climate sensitivity (low, medium or high) and GCM in order to explore the effects of climate change uncertainties on the cross-sectoral impacts and vulnerabilities. The sea-level rise scenarios in CLIMSAVE are produced following the SimCLIM model (Warrick, 2009). The projected sea-level rise values may reach 30 cm by 2050s under the high sensitivity of the A1B scenario. The projection of the four climate emission scenarios and climate sensitivity at 2020s and 2050s time slices are shown in S2 (supplementary material). However, the CLIMSAVE IAP allows exploring up to 2 metres of sea-level rise by 2100 (see Nicholls et al., 2013).

3.4.2 Socio-Economic Scenarios

The socio-economic scenarios are used to develop a series of socio-economic indicators relevant to flooding as follows:

- Change in GDP is used to reflect the change in economic conditions and how these will influence the flood damages.
- Population density: the population density is used to estimate the number of people in flood risk areas. The NUTS3 data set provides this variable for the baseline.

Four socio-economic scenarios are developed for Europe with quantifications of population change and GDP at two time slices: 2020s and 2050s (see S3, supplementary material). The GDP in ‘We are the world’ (WAW) scenario may increase to the highest level of +94% with an increase of population of 5% by 2050s. The ‘Should I stay or should I go’ (SISOG) scenario may show a decline of -36% in GDP and increase in population of +23% by 2050s. The ‘Icarus’ scenario will show no change in GDP and increase in population of +5% by 2020s and then decline to -9% by 2050s. The ‘Riders on the storm’ (ROS) will show increases of +54% and +16% by 2050s for GDP and population respectively. More details of the developed scenarios can be found in Kok et al., this volume.

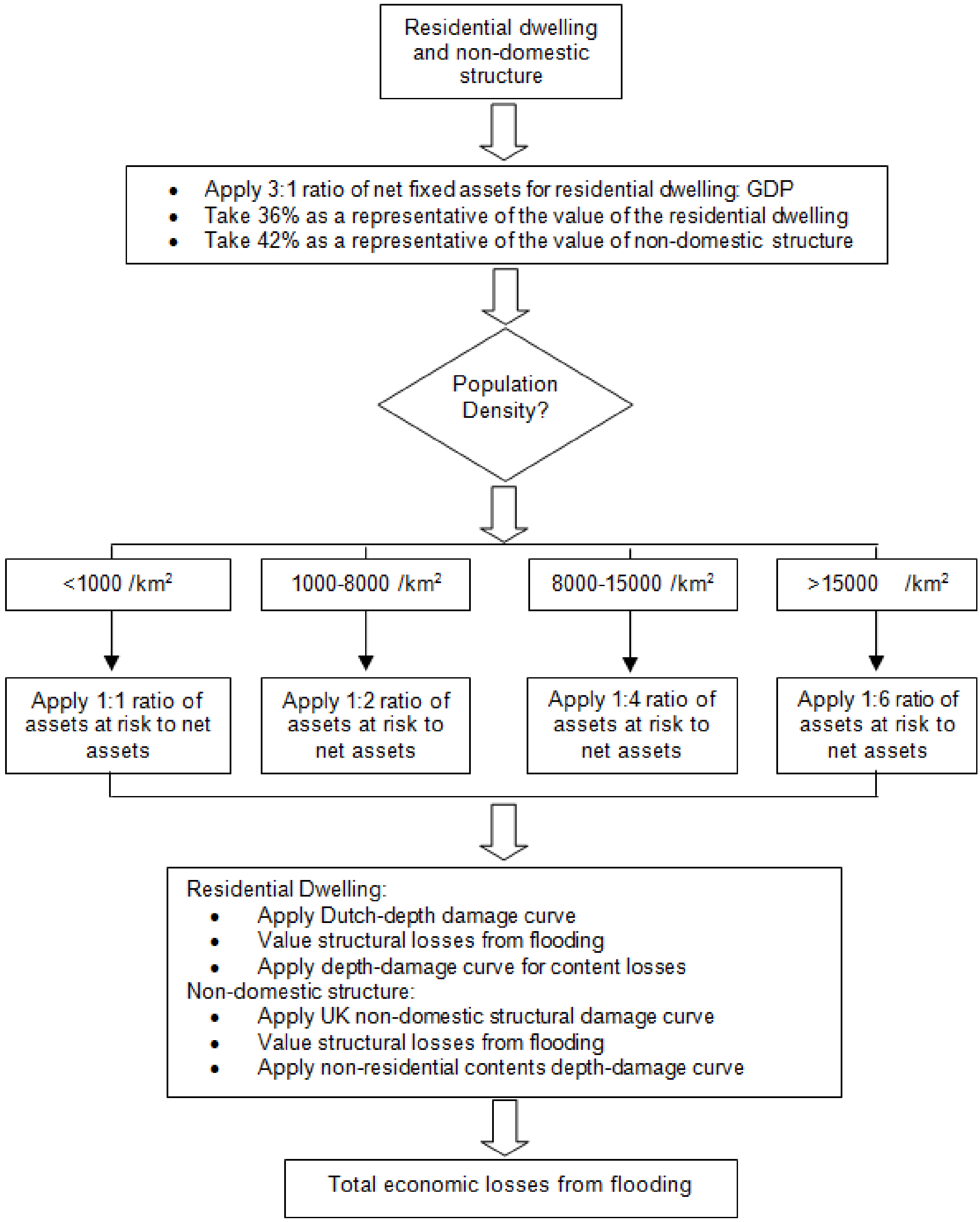


Figure 2: *Flowchart shows the flood damage calculation (adopted from Linham et al. 2010).*

3.5 Adaptation Options within the CFFlood Meta-model

The adaptation strategies investigated within the CFFlood meta-model are designed to focus on reducing flood risks through the following three measures:

a) Flood protection upgrade by 50%, 100%, 500% and 1000%: this will be applied directly to the baseline protection levels and uniformly throughout Europe. No explicit allowance for sea-level rise is included.
b) Resilience measures: considering that new properties will not be affected by flooding (e.g., by raising them above ground levels) up to a pre-defined threshold of flood event (e.g., 100 year event), while the old properties will suffer from flood damage but at a reduced rate depending on the types of resilience measures applied (e.g., using flood gates).

c) Mixed response: this provides a realistic adaptation option, where a plausible combination of flood protection improvement (i.e. 100% upgrade) and retreat of defences to maintain habitat is investigated.

4. Results and Discussions

The CFFlood model within the IAP is capable of exploring a wide range of scenario combinations by varying climate, sea-level rise, socio-economic parameters as well as the level of protection and adaptation options. However, the discussion in this paper is based on a limited number of scenario combinations for selected flood events. Table 2 shows the scenario combinations that are examined in this paper.

Table 2: *Summary of the scenario combinations presented in this paper.*

Scenario group	***Flooding type***	***Flood event***	***Time slice***	***Climate***	***Socio-economics***
1	Coastal & Fluvial	100 year	2010 (i.e. baseline year)	Baseline conditions	Baseline conditions
2	Coastal	100 year	2010 and 2100	0, 50, 100, 150, 200 cm sea-level rise values	Baseline conditions
3	Fluvial	100 year	2020s and 2050s	A1 emission scenario (CSMK3 climate model)	Four scenarios
4	Coastal and Fluvial	10, 50, 100 and 200 year	2050s	A1 emission scenario (CSMK3 climate model)	Baseline & Four scenarios

The total (i.e. coastal and fluvial) flood impacts at the baseline conditions indicates that almost 28 million people (i.e. 6% of the total population of the European Union) live within 100 year flood risk areas and the total economic damages may reach €162 Billion if these areas are flooded (See S6, supplementary material). The socio-economic impacts range from 0.74 to 17.41 million people flooded and €3 to €70 Billion losses under the 100 year flood event from the minimum to maximum estimates of protection standards. Hence, the benefit of protection is estimated at 39% and 96% for the number of people affected, while it is 57% and 98% for the flood damages under the minimum and maximum level of protections respectively.

The investigation of coastal flooding shows that at the baseline conditions there are 16.41 million people within the coastal flood risk area under the 100 year event without the effect of sea-level rise. They are strongly concentrated around the North Sea, and especially in the Netherlands. The exploratory scenarios of sea-level rise show a systematic increase in the number of people within the flood risk areas that may reach 22.9 million people (i.e. almost 40% increase from baseline) under 2 metres of sea-level rise (Figure 3). The minimum level of protection can be partially effective without the effect of sea-level rise, while it is much less effective for any sea-level rise scenario that exceeds 0.5 metre especially for sea-level rise scenarios that are equal or greater to 1 metre. For the very extreme scenario of 2 metres, the maximum level of protection has almost no effect in flood impact reduction (Figure 3).

The impacts on people due to fluvial flooding shown in Figure 4 are due to social-economic and climate changes. The number of people within the 100 year fluvial flood risk area at the baseline conditions may reach 16.35 millions. The comparison between the impacts on people at the baseline conditions in S6, Figure 3 and Figure 4 indicates that almost 4.44 million people are located within coastal and fluvial influenced flood risk areas. On the other hand, the impact on people at the European level is mainly influenced by the change in population with less influence by the climate factor (i.e. change in river flow). However, by isolating the climate factor the quantitative and spatial distribution of the fluvial flooding show a decrease in general trend under both WAW and ROS socio-economic scenarios in 2050s. Under the 'Icarus' socio-economic scenario a general trend of reduction in people affected in almost over the whole of Europe except some areas in the western and northern European regions. Under the SISOG scenario there is a considerable spatial variation in people affected as some areas in Western Europe show a reduction of the impact while other areas show an increase in flood impact - in Eastern region of Europe there is a clear increase pattern under this scenario. This can be also consistent with the fact that the increase in social pressure will lead to a larger flood impacts while a decrease in social pressure will lead to a decrease in flood impacts.

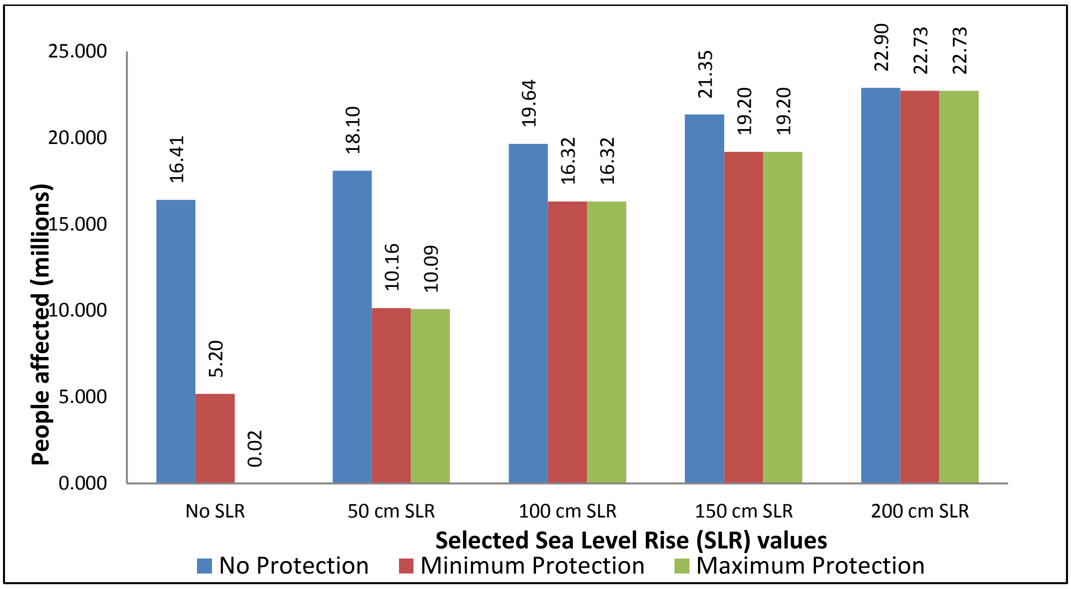
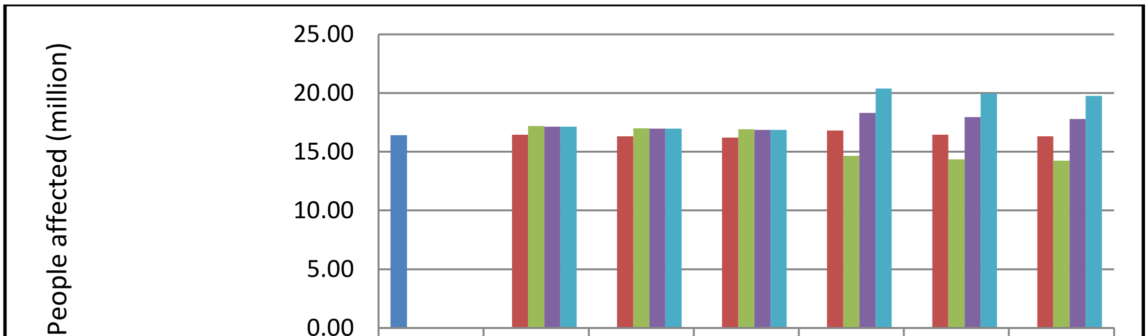


Figure 3: *People affected by coastal 100 year flooding event due to a range of sea-level rise values under baseline conditions.*



	Baseline	2020 Low	2020 Medium	2020 High	2050 Low	2050 Medium	2050 High
Baseline conditions	16.35						
we are the world		16.45	16.30	16.20	16.80	16.46	16.32
Icarus		17.18	17.01	16.91	14.65	14.34	14.23
Riders on the storm		17.13	16.96	16.87	18.31	17.95	17.79
Should I stay or should I go		17.13	16.97	16.87	20.38	19.93	19.74

Figure 4: *People affected by 100 year fluvial flooding event due to climate and socio-economic changes. Changes in impacts are mainly are due to the change in population and associated urban change.*

The impacts under four pre-defined climate and socio-economic scenarios are summarised in Figure 6. The number of people affected under the minimum protection level (i.e. the default option on the IAP) for the very extreme flood event of 200 years is the highest under the SISOG scenario, while it is the highest under the ROS for the 10 year flood event. For the 100 year event the 'Icarus' future will have the least number of people affected by flooding with a narrow range of sensitivity. This analysis incorporates the combined effects of future climate and socio-economic conditions, which include sea-level rise, precipitation, temperature and population changes.

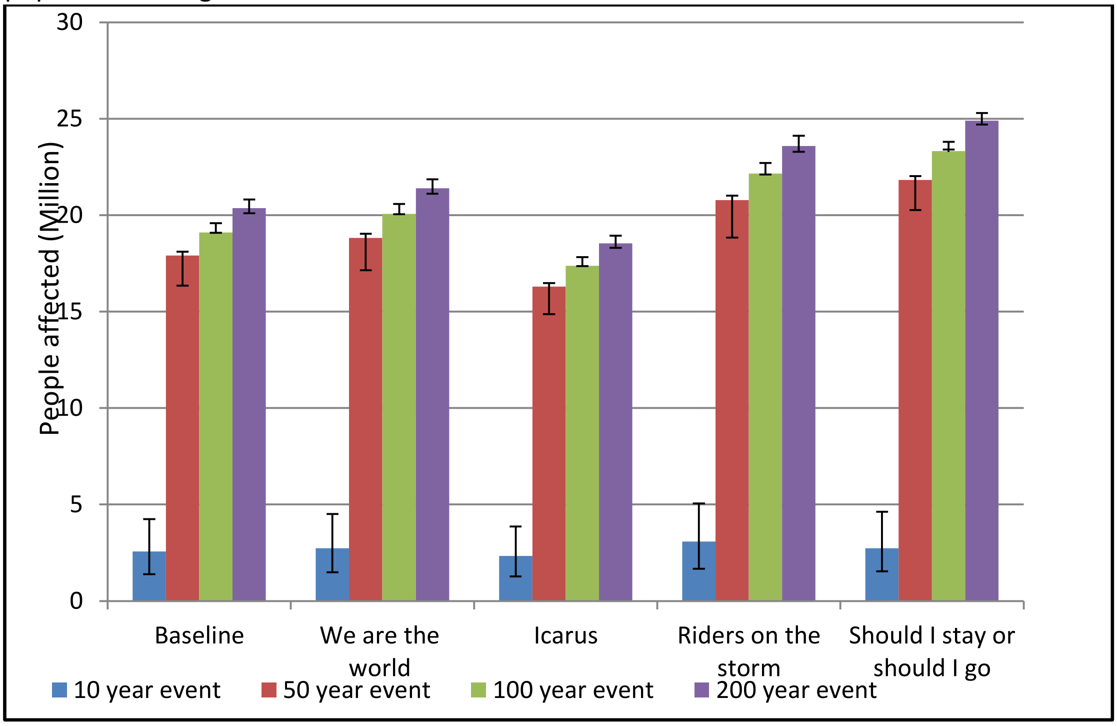


Figure 5: People affected under different flood events in 2050s (i.e. 10, 50, 100, and 200 year events) for future climate and socio-economic scenarios at the minimum level of flood protection at the middle climate variables; as well as sensitivity ranges that correspond to low and high climate variables.

The CFFlood model within the CLIMSAVE IAP can also be used to explore a range of adaptation options that are uniformly applied in Europe as explained in Section 3.6. In addition, some of the designed adaptation options will be influenced by the flood protection levels that are already in place. As the flood protection levels that are in place are not known everywhere in Europe but rather estimated based on landuse/land cover types, the outcomes of the adaptation analysis should be considered for exploratory purpose only.

To demonstrate the benefit of the designed adaptation options, an extreme combined climate and socio-economic scenario of 1 metre of sea-level rise, 25% increase of winter and summer precipitations, 3° C increase in temperature, 25% increase in population and 25% increase in GDP by 2100 is explored and the socio-economic are estimated under all adaptation options. Figure 6 shows that the explored scenario will increase the people at risk of flooding from almost 28 million (at the baseline) to 41 million people, while the minimum level of flood protection reduces the impact to almost 17 million at the baseline conditions and 37 million under the explored scenario. Thus, while the performance of the current defence systems under current conditions can be effective, it is not effective under the investigated extreme scenario and more aggressive policies for reducing flood risk are needed. The analyses indicate that a significant increase in the level of flood protection (i.e. 500% and above) is required in order to reduce the impacts to the baseline level. The implementation of resilience measures (i.e. elevated buildings) at the minimum level of flood protection may perform well but they are not enough on their own to reduce flood impacts to the baseline level. The impacts of realigning flood defences on socio-economic impacts are negligible as these adaptation options are mainly designed for reducing environmental impacts and the defence realignment is designed to take place in rural areas that are characterised with very low population density.

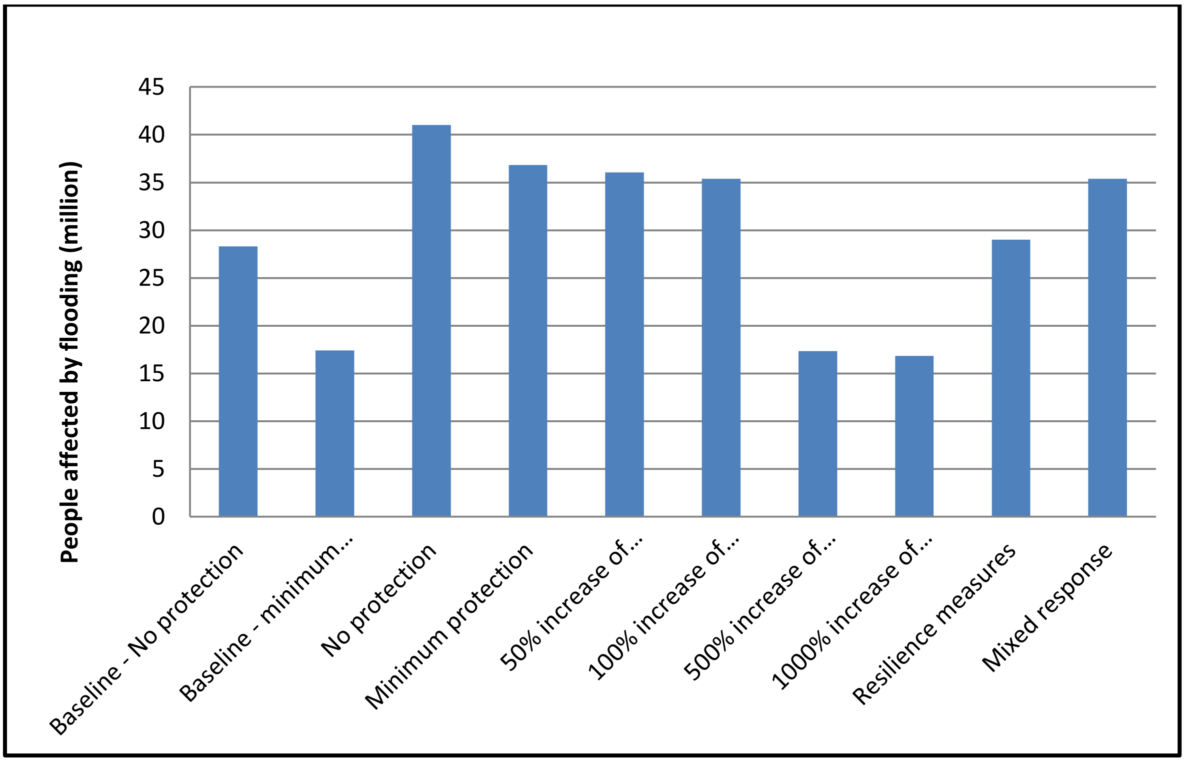


Figure 6: *People affected by 100 year flood event under a range of adaptation options including: increasing the flood protection level by 50%, 100%, 500%, and 1000% from the minimum flood protection level, and a mixed response of increasing flood protection by 100% and realignment of defences - the investigated scenario includes 1 meter sea-level rise, 25% increase in the winter and summer precipitations, 25% population, 25% increase in GDP.*

5. Conclusions and Future Work

The socio-economic and environmental impacts under current and plausible future conditions can be investigated using the CFFlood meta-model within the CLIMSAVE IAP. The flood meta-model is capable of estimating coastal and fluvial flood impacts – it accounts for relative sea level and change in the extreme fluvial flow due to change in future climates (i.e. temperature and precipitation) as well as socio-economic changes such as population and GDP. The CFFlood model also allows exploration of a range of adaptation options. The level of flood protection is essential to estimate the actual socio-economic flood impacts. A method based on land use/cover type is used to estimate the level of flood protection in Europe; this allows for three levels of protection to be explored (i.e. no protection, minimum protection and maximum protection). The analysis of a limited set of results reveal some key findings with regards to current as well as future flood impacts. These include the following:

1. Almost 28 million people (i.e. 6% of European population) are at risk of flooding (based on the 100 year event) – these include people residing in fluvial, coastal, and mixed coastal and fluvial floodplains.
2. The estimated land use/cover based protection levels indicate that the minimum level of protection can reduce the socio-economic impacts by 39%, while the maximum protection level can almost eliminate the impacts at the baseline conditions (i.e. 96% reduction of people affected).
3. Future sea-level rise will cause a significant increase in socio-economic impacts in coastal areas and consequently more aggressive adaptation measures are required to adapt and mitigate to future conditions.
4. Future climate conditions may not cause a net increase in the impacts of fluvial flooding at the European scale, but the spatial distribution of risk will change from southern regions towards northern and eastern regions under the scenarios considered here (see S7, supplementary material).

5. Future economic conditions under the four socio-economic scenarios will have a major influence on the level of flood damage. Under some of the scenarios such as 'Icarus' and SISOG the reduction in economic impact is significant and it is due to declining economies. The highest economic damages are likely under the WAW scenario.
6. In regards to adaptation, extreme future climate conditions combined with an increase in human pressures will lead to significant increases in the socio-economic impacts. To reduce such impacts a major increase in flood protection is required such as 500% increase of current protection standards and above in order to achieve a reduction in impacts to the baseline levels.

Although the CFFlood offers a unique opportunity to quantify the socio-economic impacts of coastal and fluvial flooding at the European scale for current as well as future conditions, there are a number of improvements that can be achieved in future research. These include improving the flood protection dataset to represent the actual flood protection levels. The explored adaptation measures can also be improved to allow more detailed flood protection measures with spatial variation across Europe including the incorporation of more flood resilience measures.

Acknowledgments

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Cross-sectoral impacts of climate change and socio-economic change for multiple, European land- and water-based sectors

P.A. Harrison[1], R. Dunford[1], C. Savin[2], M.D.A. Rounsevell[3], I.P. Holman[4], **A.S. Kebede**[5], B. Stuch[6]

[1] *Environmental Change Institute, Oxford University Centre for the Environment, South Parks Road, Oxford, OX1 3QY, United Kingdom, Tel. +44 (0) 1865 275848, Email: Paula.Harrison@ouce.ox.ac.uk*
[2] *Tiamasg Foundation, Foundation, Sfintii Voievozi 6, 010963 Bucharest, Romania*
[3] *School of GeoSciences, The University of Edinburgh, Drummond Street, Edinburgh, EH8 9XP, UK*
[4] *Cranfield Water Science Institute, Cranfield University, Cranfield, Bedford, MK43 0AL, UK*
[5] *Faculty of Engineering and the Environment and Tyndall Centre for Climate Change Research, University of Southampton, Highfield, Southampton SO17 1BJ, UK*
[6] *Center for Environmental Systems Research, University of Kassel, Germany*

Abstract

Understanding cross-sectoral interactions is important in developing appropriate adaptation strategies to climate change, since such insight builds the capacity of decision-makers to understand the full extent of climate change vulnerability, rather than viewing single sectors in isolation. A regional integrated assessment model which captures interactions between six sectors (agriculture, forests, biodiversity, water, coasts and urban) was used to investigate impacts resulting from a wide range of climate and socio-economic scenarios. Results show that Europe will be significantly influenced by future change with between 79% and 91% of indicator-scenario combinations found to be statistically significantly different from the baseline. Urban development increases in most scenarios across Europe. The number of people affected by a 1 in 100 year flood increases in western and northern Europe. Biodiversity vulnerability and water exploitation both increase in southern and eastern Europe. Changes in land use (intensive farming, extensive farming, forests and unmanaged land) vary depending on the scenario, but food production generally increases across Europe at the expense of forest area to satisfy the demand from an increasing population. The results show that non-climatic pressures, such as future socio-economic change, may be at least as, if not more, important than climate change, but there are many compounding and interacting effects. This highlights the importance of quantifying future impacts across multiple sectors and for both climate and socio-economic change to more fully capture uncertainties which can better inform the assessment of robust adaptation options.

Keywords: Climate change, socio-economic change, impacts, integrated assessment, uncertainty

1. Introduction

Numerous models have been developed and applied to study climate change impacts on specific sectors at a range of scales, for example, agriculture (Lobell et al. 2006; Soussana et al. 2010), forestry (Bergh et al. 2003; Rasche et al. 2013), biodiversity (Harrison et al. 2008; Keith et al. 2008), water (Lehner et al. 2006; Alcamo et al. 2007) and coasts (Nicholls and Tol 2006). However, most models treat each sector independently thereby ignoring important feedbacks and cross-sectoral interactions. Cross-sectoral interactions are important since changes in one sector can affect another sector either directly, e.g. changes in land use affect regional hydrology or biodiversity, or indirectly through policy, e.g. measures designed for coastal flood defence also impact on coastal habitat (Holman et al. 2008a,b). Ignoring cross-sectoral interactions can lead to either over- or under-estimation of climate change impacts and the need for adaptation in limiting societal vulnerability (Carter et al. 2007). Yet in spite of this only a few climate impacts studies adopt a cross-sectoral approach.

At the global scale, Integrated Assessment Models (IAMs) (e.g. van Vuuren et al. 2011), often combined with computable general equilibrium (CGE) models (e.g. Hertel et al. 2011), are used to project impacts across a range of sectors in climate change assessments. IAMs and CGE models have acknowledged strengths in providing comprehensive cross-sectoral analyses, but have been criticised for the simplistic way in which they represent some processes and a lack of spatial differentiation (Rounsevell et al. 2013). CGE models, for example, are based on sectors rather than geographic space and are rarely resolved below the level of world regions or countries. Busch (2006) demonstrated the large divergence between IAMs and regional scale models in scenario studies of land use change in Europe. Even the direction of change was found to be considerably different with, for example, IAMs projecting increases in cropland areas, but regional scale models projecting decreases (Busch 2006).

However, understanding global environmental changes requires understanding intrinsically regional phenomena within an integrated framework (Hibbard and Janetos 2013). Although there are many published regional integrated assessment studies, there are relatively few that link impact models across sectors (e.g. Rounsevell et al. 2006 - agriculture and biodiversity; Kirchen et al. 2008 - multiple urban infrastructure types; Xiong et al. 2010; Barthel et al. 2012 - water and agriculture; Baruffi et al. 2012 - surface and groundwater resources) and fewer still that both integrate between multiple sectors and consider climate and socio-economic change together (e.g. Holman et al. 2005; Holman et al. 2008a; Harrison et al. 2013).

Climate change impacts will interact with those associated with continuing socio-economic changes, in potentially complex, non-additive ways. Since the future is unknown, scenario analysis is often used in climate change assessments to account for alternative, future socio-economic development pathways and their implications for climate change (Rounsevell and Metzger 2010). Scenarios encapsulate the uncertainties associated with social and political changes that are impossible to foresee through a series of 'what if?' experiments that explore plausible, i.e. not impossible, future states of the world or a region. However, the scenario approach can itself introduce other uncertainties deriving from the limits to knowledge, personal judgement (including beliefs and axiomatic preconceptions), and the quantification of scenarios with models (Rounsevell and Metzger, 2010). However, whilst such limitations are known, scenarios still offer a tractable and enriching approach to explore alternative futures, especially when applied within a stakeholder, participatory context. The development of scenarios with stakeholders enables the exploitation of a wide range of tacit knowledge and experience, especially at the regional scale (e.g. Gramberger et al. this volume; Kok et al. this volume).

This paper examines the cross-sectoral implications of different climate and socio-economic scenarios in Europe. A regional integrated assessment (IA) model which captures interactions between six sectors (agriculture, forests, biodiversity, water, coasts and urban) is used to investigate both direct and indirect sectoral impacts resulting from different climate and socio-economic scenario combinations. The study aims to provide new insights into the complex interactions between different sectors under different scenario futures. It also highlights how the inclusion of non-climate pressures, in combination with climate pressures, affects the robustness of projected impacts across multiple sectors.

2. Methods

2.1 The CLIMSAVE IA Platform

The CLIMSAVE[31] IA Platform is an interactive, exploratory, web-based tool for assessing climate change impacts and vulnerabilities on a range of sectors, including agriculture, forests, biodiversity, coasts, water resources and urban development (Harrison et al. 2013; Harrison et

[31] CLimate change Integrated Methodology for cross-Sectoral Adaptation and Vulnerability in Europe

al. this volume). The Platform integrates a suite of sectoral models to simulate spatially the negative or positive effects of different climate and socio-economic scenarios on these sectors across Europe, allowing the evaluation of cross-sectoral benefits, conflicts and trade-offs. In order to enable greater complexity of model linkages to be represented within the IA Platform and facilitate a relatively fast run time, a meta-modelling approach was used based on computationally efficient or reduced-form models that emulate the performance of more complex models (Harrison et al. 2013). The Platform operates at a spatial resolution of 10 arcmin x 10 arcmin (approximately 16km x 16km in Europe) and produces outputs of both sector-based impact indicators and ecosystem services in order to link climate change impacts directly to human well-being.

2.2 Climate and Socio-Economic Scenarios

The CLIMSAVE IA Platform incorporates a range of climate and socio-economic scenarios that can be selected either independently or in combination for two future timeslices (either the 2020s or 2050s). This allows exploration of how impacts and cross-sectoral interactions change for different scenario combinations.

2.2.1 Climate Scenarios

The climate change scenarios are based on the IPCC emissions scenarios (A1b, A2, B1 or B2), a range of climate sensitivities (low, medium or high) and a number of global climate models (GCMs). Five GCMs are included within the IA Platform chosen using an objective method to represent as much uncertainty as possible due to between-GCM differences (MPEH5, CSMK3, HadGEM, GFCM21 and IPCM4) (see Dubrovsky et al. this volume for further details).

Projections of Europe-wide area-average temperature change range from 1.1 to 4.9^{o}C in winter and from 1.0 to 3.6^{o}C in summer in the 2050s. Projections for precipitation change range from increases of between 1.1 and 12.5% in winter and decreases of between 2.0 and 29.5% in summer (Table S1). The pattern of temperature and precipitation changes differs according to the GCM (Figure S1).

2.2.2 Socio-Economic Scenarios

The CLIMSAVE IA Platform contains four socio-economic scenarios that were developed by stakeholders in a series of three participatory scenario workshops (see Gramberger et al. this volume). The scenario logic is structured along two dimensions: “Economic Development” and “Solutions by Innovation”. The scenarios cover a range of drivers including social, economic, cultural, institutional and political developments in a set of integrated future outlooks (Kok et al. this volume; Table S2).

The most prosperous future scenario, combining high levels of innovation and gradual economic development is *We are the World (WRW)*; where effective governments change the focus from GDP to well-being, which leads to a redistribution of wealth, and thus to less inequality and more (global) cooperation. By contrast, governments in the *Icarus* scenario focus on short-term policy planning, which together with a gradually stagnating economy, leads to the disintegration of the social fabric and to a shortage of goods and services. The *Should I Stay or Should I Go (SoG)* scenario is characterised by actors failing to address a rollercoaster of economic crises, which leads to an increased gap between rich and poor, to political instability and to conflicts. The *Riders on the Storm (Riders)* scenario is also adversely affected by continual economic crises. However, actors successfully counter this situation by investing in renewable energy and green technologies.

2.3 Model Runs and Analysis

The CLIMSAVE IA Platform was run for 50 scenarios for the 2050s timeslice to explore the effects of climate change and socio-economic change uncertainties on cross-sectoral impacts. The scenario combinations can be categorised into three groups:

- Climate scenarios for the five GCMs combined with a low emissions scenario (B1), low climate sensitivity and baseline socio-economics (5 runs);
- Climate scenarios for the five GCMs combined with a high emissions scenario (A1), high climate sensitivity and baseline socio-economics (5 runs); and
- Climate scenarios (10 runs above) combined with the four socio-economic scenarios (40 runs).

Each scenario run was analysed for 11 sectoral indicators (Table S3): 1) area of artificial surfaces; 2) number of people flooded in a 1 in 100 year event; 3) food production; 4) area of intensive farming; 5) area of extensive farming; 6) forest area; 7) area of unmanaged land; 8) land use intensity index; 9) biodiversity vulnerability index; 10) water exploitation index; and 11) irrigation uptake. Each indicator was analysed for the whole of Europe and for four catchment-based regions: northern, western, eastern and southern Europe (Figure S2). For each combination of indicator, scenario and region, a number of summary statistics were computed from the 23,871 land grid cells: mean, median and the 5th, 25th, 75th and 95th percentiles. A paired t-test was also performed on each indicator in each scenario and region to determine if it was statistically different from the baseline at a 5% significance level.

3. Results

3.1 Statistical Significance of Impacts

For the runs based on just climate change scenarios, 82.7% of indicators are statistically different from the baseline at the European scale (Table 1a). Those found not to be statistically significantly different include the urban scenarios which have no climate-driven response, many of the scenarios for food production and a single scenario for biodiversity. Many of the runs also showed significant differences from baseline at the regional scale: northern Europe is the most similar to baseline followed by western and eastern Europe, with southern Europe showing the largest changes where 90.9% of indicators are statistically different to baseline. For the runs based on combined climate and socio-economic scenarios, Icarus stands out as having the lowest proportion of indicators that are statistically different from the baseline at the European and regional scales, except in northern Europe. The other three scenarios have relatively similar high levels of difference from baseline, but with regional differences (Table 1a). In contrast to the climate-only scenarios, northern Europe shows the most statistical differences to baseline for all, but the SoG scenario.

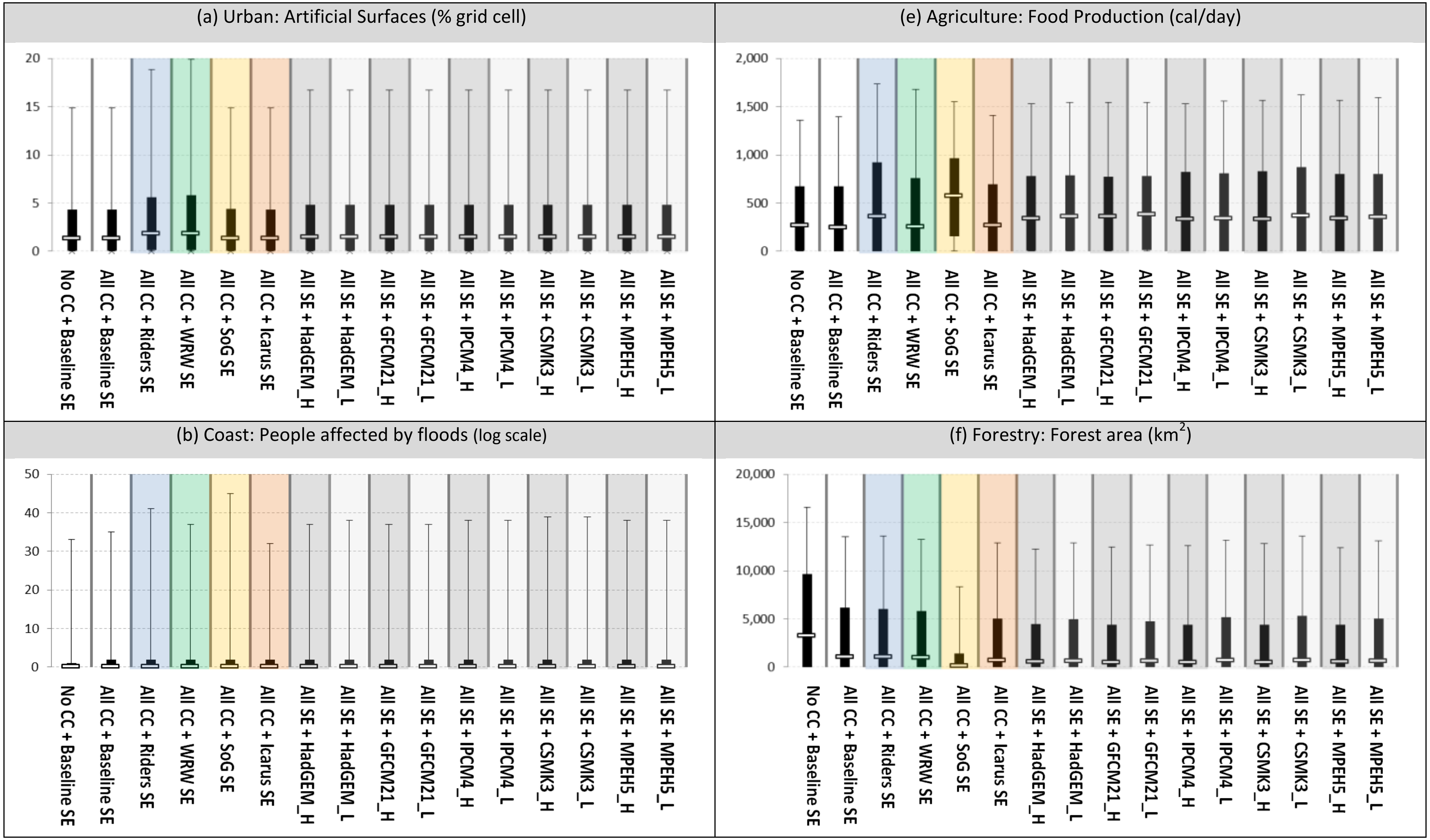
3.2 Sectoral Changes at a European Scale

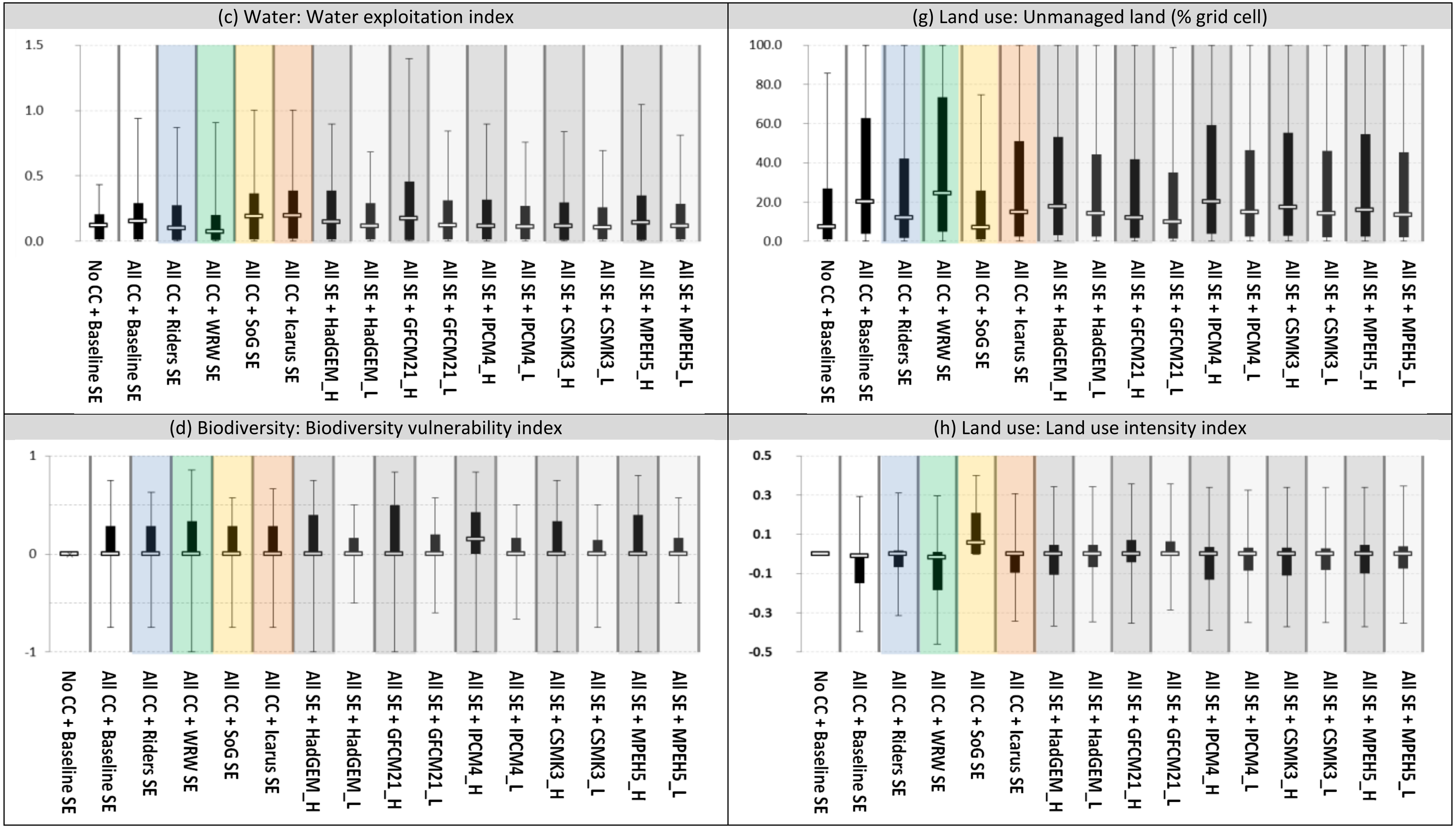
At the European scale it is clear that the different sectors respond very differently to different drivers. Table 1b provides a statistical summary of the mean change from baseline of each indicator across groups of the scenarios, highlighting the maximum and minimum values produced in both (i) climate-only and (ii) combined climate and socio-economic scenarios. However, focusing only on changes in the mean hides a lot of change that takes place in the distributions, particularly at the extremes. To address this Figure 1 extends the analysis and summarises the full distribution of the indicators at the European scale as box and whisker plots focusing on the median, 5th, 25th, 75th and 95th percentiles of the distribution for eight indicators in the 10 climate scenarios runs (and summarised across all these runs as 2050 BL) and 40 combined climate and socio-economic scenario runs (summarised for the 10 runs undertaken for each of the four socio-economic scenarios) (see Figure S3 for box and whisker plots for the four regions). Further summaries based on changes in the 25th and 75th percentiles are given by region in Figure 2.

Table 1: *Results from the scenario analysis: (a) average percentage of indicators that are statistically significantly different from the baseline for the climate-only scenarios and the combined climate and socio-economic scenarios; and (b) maximum and minimum values of the mean change from baseline for groups of scenarios for the 2050s. Values are presented by indicator and region for climate scenarios using baseline socio-economic values (i.e. driven by climate alone) and combined climate and socio-economic scenarios (i.e. averaged across the four socio-economic scenarios). Grey shaded cells are used to identify indicators where the maximum and minimum trends are in different directions; where this is not the case the direction of the trend may be seen as robust.*

(a)	**Climate scenarios**	**Climate & socio-economic scenarios**			
		Riders	**WRW**	**SoG**	**Icarus**
Europe	82.7	88.2	90.0	90.9	79.1
Western Europe	84.5	90.0	87.3	89.1	86.4
Southern Europe	90.9	90.0	89.1	90.9	82.7
Eastern Europe	87.3	88.2	90.0	90.9	82.7
Northern Europe	83.6	90.0	90.9	83.6	90.0

(b) Indicator	**Climate only scenarios**										**Combined climate and socio-economic scenarios**									
	Europe		**West**		**South**		**East**		**North**		**Europe**		**West**		**South**		**East**		**North**	
	Min	**Mix**	**Min**	**Max**	**Min**	**Max**	**Min**	**Max**	**Min**	**Max**	**Min**	**Max**	**Min**	**Max**	**Min**	**Max**	**Min**	**Max**	**Min**	**Max**
Artificial surfaces (%)	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	1.2	0.0	2.5	0.0	1.0	0.0	0.4	0.0	0.6
People flooded (1000s people)	0.5	0.9	1.7	2.6	0.5	1.1	-1.0	-0.4	0.1	0.2	-0.2	2.7	0.5	5.3	-0.2	2.5	-1.9	7.8	0.0	0.6
Biodiversity VI (-)	0.0	0.1	0.0	0.2	0.2	0.4	0.0	0.3	-0.4	-0.1	0.0	0.1	0.0	0.3	0.1	0.5	0.0	0.4	-0.4	0.0
Intensively farmed (%)	-3.6	-0.6	-5.7	1.9	-19.0	-9.1	-10.2	-6.0	5.4	10.0	-5.5	26.7	-9.0	23.7	-20.7	21.4	-20.5	28.1	3.6	31.7
Extensively farmed (%)	-7.1	-2.0	0.8	7.7	-8.3	4.2	1.6	8.3	-20.3	-17.9	-7.8	5.3	-3.8	7.2	-9.6	7.2	-3.5	12.4	-20.5	4.6
Food production (%)	228.4	280.2	327.9	431.2	275.5	337.0	153.8	236.1	113.5	209.2	199.2	353.0	302.4	502.5	197.8	397.7	156.8	349.9	101.5	286.3
Forest area (km^2)	-1995	-1389	-2999	-1799	-1768	-904	-1799	-1072	-1817	-1059	-4159	-1451	-4340	-1822	-2977	-959	-4875	-653	-4279	-945
Unmanaged land (%)	10.7	20.5	3.5	14.2	9.3	33.9	4.9	15.0	19.0	22.3	-1.5	22.5	-0.1	16.4	-0.2	33.4	-0.2	25.7	-4.4	26.2
Intensity index (-)	-0.1	0.0	-0.1	0.0	-0.2	-0.1	-0.1	0.0	-0.1	-0.1	-0.1	0.1	-0.1	0.1	-0.2	0.1	-0.2	0.1	-0.1	0.2
Water Exploitation Index (%)	0.0	0.2	0.0	0.1	0.1	0.6	0.1	0.3	0.0	0.0	0.0	0.3	-0.1	0.2	0.1	0.7	0.0	0.4	0.0	0.0
Irrigation usage (10^3 m^3/yr)	0.5	0.9	0.0	0.3	1.7	2.7	0.7	1.5	0.0	0.0	0.2	2.4	0.0	3.1	0.4	5.3	0.3	4.0	0.0	0.0


(a) Urban: Artificial Surfaces (% grid cell)
(e) Agriculture: Food Production (cal/day)
(b) Coast: People affected by floods (log scale)
(f) Forestry: Forest area (km2)
No CC + Baseline SE
All CC + Baseline SE
All CC + Riders SE
All CC + WRW SE
All CC + SoG SE
All CC + Icarus SE
All SE + HadGEM_H
All SE + HadGEM_L
All SE + GFCM21_H
All SE + GFCM21_L
All SE + IPCM4_H
All SE + IPCM4_L
All SE + CSMK3_H
All SE + CSMK3_L
All SE + MPEH5_H
All SE + MPEH5_L



(c) Water: Water exploitation index
(g) Land use: Unmanaged land (% grid cell)
(d) Biodiversity: Biodiversity vulnerability index
(h) Land use: Land use intensity index
No CC + Baseline SE
All CC + Baseline SE
All CC + Riders SE
All CC + WRW SE
All CC + SoG SE
All CC + Icarus SE
All SE + HadGEM_H
All SE + HadGEM_L
All SE + GFCM21_H
All SE + GFCM21_L
All SE + IPCM4_H
All SE + IPCM4_L
All SE + CSMK3_H
All SE + CSMK3_L
All SE + MPEH5_H
All SE + MPEH5_L

Figure 1a-h: *European level box and whisker plots are based on grid cell values and show combinations of climate change (CC) and socio-economic (SE) scenarios for eight indicators. The plots show distributions for: baseline (No CC + Baseline SE; single run); the ten 2050s climate scenarios combined with the five socio-economic scenarios (All CC + Baseline/Riders/WRW/SoG/Icarus; 10 runs each) and the Low (_L) and High (_H) emissions scenarios of the five climate models (HadGEM, GFCM21, IPCM4, CSMK3 and MPEH5) combined with the four socio-economic scenarios (All SE + HadGEM_H, etc.; 4 runs each). The whiskers show the 5^{th} and 95^{th} percentiles whilst the boxes show the 25^{th} and 75^{th} percentiles. The median is marked with a white dash in the centre of the box. Note for scaling reasons that values may extend off the displayed graph.*

	All CC + Baseline SE					All CC + Riders SE					All CC + WRW SE					All CC +SoG SE					All CC + Icarus SE				
	Eu	N	W	E	S	Eu	N	W	E	S	Eu	N	W	E	S	Eu	N	W	E	S	Eu	N	W	E	S
Artificial surfaces (%)	∘	∘	∘	∘	∘	+	↑	↑	+	+	+	↑	↑	+	+	∘	∘	∘	+	∘	∘	∘	∘	∘	∘
People flooded (1000s people)	↑	∘	+	↑	↑	↑	∘	+	↑	↑	↑	∘	+	↑	↑	↑	∘	+	↑	↑	↑	∘	∘	↑	↑
Water Exploitation Index (-)	↕	-	+	+	↑	↕	-	-	↕	↑	-	-	-	↓	↑	↑	+	↑	+	↑	↑	+	↑	+	↑
Irrigation usage (m^3/yr)	↑	∘	∘	-	↑	↑	∘	↑	↑	↑	↑	∘	↑	+	↑	∘	∘	∘	↓	↑	↑	∘	↑	↓	↑
Biodiversity VI (-)	+	-	+	+	↑	+	-	+	+	+	+	-	+	+	↑	+	-	+	+	+	+	-	+	+	+
Food production (cal/day)	↓	↑	-	>	↓	↕	+	+	↕	↕	↕	↑	-	↓	↕	↑	↑	↑	↑	↑	↓	∘	+	-	↓
Intensively farmed (%)	∘	↑	-	+	↓	+	∘	+	+	-	-	↑	-	↓	↓	↑	↑	↑	↑	↑	+	∘	↑	+	↓
Extensively farmed (%)	↓	↓	↑	↓	↓	-	↓	↑	↑	↓	↓	↓	↕	↓	↓	-	+	-	↓	↓	-	↓	↑	+	↓
Forest area (km^2)	↓	-	↓	+	↓	↓	-	↓	+	↓	↓	-	↓	+	↓	↓	↓	↓	↓	↓	↓	-	↓	+	↓
Unmanaged land (%)	↑	↑	↑	↓	↑	↑	↑	↑	↓	↑	↑	↑	↑	↕	↑	∘	-	-	↓	∘	↑	↑	↑	↓	↑
Intensity index (-)	-	-	-	-	-	-	-	+	∘	-	-	-	-	-	-	+	+	+	+	+	-	-	+	-	-

↑	Increase >50% in either the 25^{th} or 75^{th} percentile with a non-negative change in the other
+	Increase >5% in either the 25^{th} or 75^{th} percentile with a non-negative change in the other
∘	Change < ±5% in both the 25^{th} or 75^{th} percentile
-	Decrease >5% in either the 25^{th} or 75^{th} percentile with a non-positive change in the other
↓	Decrease >50% in either the 25^{th} or 75^{th} percentile with a non-positive change in the other
>	Decrease > 5% in 75^{th} percentile and Increase > 5% in 25^{th} percentile – contracting distribution
↕	Increase > 5% in 75^{th} percentile and decrease > 5% in 25^{th} percentile – widening distribution

Figure 2: *Cross-sectoral summary of changes in the 25^{th} and 75^{th} percentiles of indicator distributions for Europe and the four regions for the 2050s. All CC + Baseline SE is based on the climate-only scenarios with baseline socio-economic scenarios. All CC + Riders, WRW, SoG and Icarus are based on the combined climate and socio-economic scenarios.*

3.2.1 Urban Sector: Area of Artificial Surfaces

The amount of artificial surfaces within a scenario is driven solely by changes within the socio-economic scenarios; there is no influence of climate. As such, Figure 1 shows identical plots for Baseline and the climate-only scenarios (BL2050). The key drivers of urban growth are population and GDP. WRW shows the most growth as both population and GDP growth are high. The second utopian scenario, Riders, also shows higher levels of artificial surfaces as it has moderate population growth and high GDP. The dystopian scenario, SoG, has high population growth, but low GDP and, as such, shows only limited urban growth in eastern Europe (Figure 2). In contrast, the Icarus scenario shows no trends >5% at either the 25th or the 75th percentile (Figure 2) because population declines in this scenario, whilst GDP stays at current levels.

From a regional perspective, in both Riders and WRW the changes in northern and western Europe are proportionally greater (>50% increase) than those in southern and eastern Europe (5-50%; Figure 2). However, very different magnitudes of growth occur: in northern Europe there is a small increase from a low baseline, e.g. the 75th percentile increases from 0.72% to >1.1%, whereas in western Europe the increase is from 7.4% (due to several large cities, such as London, in this region) to >10%. In southern Europe, the 75th percentile increases from 2.93% to >3.7% (an increase of ≥29%). Eastern Europe, however, shows very little urban growth; despite having a high baseline 75th percentile (5.6%); this increases by <10% even in the utopian scenarios, which arises from the lower GDP in the eastern European countries.

3.2.2 Coastal Sector: Number of People Flooded in a 1 in 100 year event

At the European scale there is very little change in the number of people flooded. However, there are changes in the extreme values of the number of people affected by flooding and the 75th percentile increases from 1 to 2000 people irrespective of the socio-economic and climatic scenario (Figure 1). At the 95th percentile, there is notable variation between the socio-economic scenarios: values are higher in the SoG and Riders scenarios, and lowest in the Icarus scenario. This reflects the changes in populations assigned to these scenarios: in SoG and Riders the population increases by 23 and 16, respectively, whilst in Icarus European population declines by 9%. The flooding indicator is also affected by the climate scenarios, as shown by the small differences in the 95th percentiles in Figure 1. These changes reflect the relatively minor increases in sea-level by the 2050s (18-21 cm) under the different emissions scenarios as well as differences in the levels of fluvial flooding as a result of changing patterns of precipitation.

Despite the relatively uniform changes in the 75th percentile at the European scale there are considerable inter-regional differences. Western, eastern and southern European regions generally show significant increases in the number of people flooded whilst northern Europe shows no real change. This reflects patterns of urban development, which in turn are heavily driven by baseline population; with fewer people and a lower population growth in northern Europe.

3.2.3 Land use-related Indices: Food Production, Intensive and Extensive Farming, Forest Areas, Unmanaged Land and Land use Diversity Index

Food production increases across Europe and the regions in terms of the mean in both the climate-only and the combined climate and socio-economic scenarios (Table 1b). Regionally, western Europe shows the greatest mean increase in food production, whilst northern Europe shows the least. The socio-economic scenarios exacerbate the extremes of the indicator distributions (Figure 1). SoG results in significant increases in food production at both the 25th and the 75th percentiles in all regions (Figure 2). Conversely, at the European scale, Riders shows significant increases at the 75th percentile, but does not have a corresponding increase at the 25th percentile. As such SoG’s median is considerably higher than all of the other socio-economic scenarios, although its 95th percentile is lower than both Riders and WRW. This is a good reflection of the scenario storylines. SoG is a particularly extreme scenario with a significant increase in population (+23%), but no successful innovation. As a result, agricultural mechanisation increases slowly relative to the other scenarios and water savings from technological change, irrigation efficiency and agricultural yields all decline. These factors lead to a world in which food production is the key priority. This has impacts on all other land use sectors and significant increases are noted in terms of the amount of intensive farming and the intensity index. Extensive farming declines in western Europe (replaced by intensive farming), and increases in northern Europe (where it replaces forestry and unmanaged land). Forest cover declines in all areas, particularly in the north and east, and the positive trends in unmanaged land in the north, south and west identified in the climate-only scenarios are absent or negative in all regions as the scenario makes use of all available land to meet the pressing food demand.

Conversely, in the WRW and Riders scenarios population increase is lower (+5% and +16%, respectively), and technological innovations lead to improvements in agricultural mechanisation, water savings, irrigation efficiency and agricultural yields. In addition there are dietary changes away from the consumption of meat. These factors combine to put less pressure on the system to produce food. As such, at a European scale both scenarios show mixed trends with some areas producing more food than they are able to within SoG (due to successful innovations), but without the extreme levels of conversion of all other land uses that are seen in SoG. Unmanaged land shows positive trends in northern, southern and western Europe, particularly in the WRW scenario, and mixed/negative trends in WRW/Riders, respectively, in eastern Europe (where conversion to farmland is taking place). As a result land use intensity generally reduces.

It is notable that forest area declines in northern, southern and western Europe in all scenarios and only slightly increases in eastern Europe in Riders, WRW and Icarus. The decline in forest area results from a number of factors. Firstly, profitability: in some scenarios, particularly those as extreme as SoG, forest land is simply not as profitable as agricultural land; in these scenarios trees are replaced by agriculture. Secondly, CO_2 increase: timber yield increases due to increasing levels of CO_2. This means that less forest area is required to produce the same amount of timber. As such, profitability is affected and the amount of land required for forests declines. Thirdly, climatic suitability: some areas change in terms of their climatic suitability for the currently planted species. In these cases, the land use no longer remains forest and is classified as unmanaged land. A combination between these three factors drives the decline in European forests seen in the majority of scenarios.

3.2.4 Biodiversity: Biodiversity Vulnerability Index (BVI)

In the climate-only scenarios, biodiversity vulnerability increases in southern, eastern and western Europe, but improves in northern Europe. Trends in terms of the mean are greatest in the south and east (Table 1b). In terms of climate drivers, the low emissions scenarios lead to lower levels of biodiversity vulnerability, whilst the GFCM21 and IPCM4 climate models result in the greatest vulnerability. However, the way in which vulnerability is manifest is different. For all scenarios, except the high emissions IPCM4, the median value and the 25th percentile are both zero indicating that at least 25% of the grid cells show no change in terms of the total number of vulnerable species (Figure 1). However, in the IPCM4 scenario, the 25th percentile is zero and the median suggests that for over 50% of grid cells the BVI is greater than 0.2 (reflecting that 20% of species no longer have appropriate climate-habitat space). Interestingly, the GFCM21 scenario has a lower median, but more high values: 25% of the data have a BVI > 0.5. The socio-economic scenarios widen the range between the extremes compared to the runs driven by climate alone. WRW stands out as having the broadest range of values: it has both the highest and the lowest vulnerability in terms of the 5th and 95th percentiles. Conversely, SoG has the least vulnerability in terms of the 95th percentile, but also the least improvement in vulnerability in terms of the 5th percentile.

The strong influence of both climate and socio-economics is expected as biodiversity vulnerability reflects the output of bioclimatic envelope modelling combined with habitat masks from the land use allocation model. Vulnerability increases wherever the climate becomes unsuitable or the appropriate habitat for a species is lost. Thus, SoG's drive towards food production provides positive benefits in terms of broadening the area of Europe with habitat for species associated with arable farming, such as those that rely on cereal field margins. This is partly at the expense of species associated with forests as is shown by the 95th percentile of vulnerability in northern Europe being notably greater than any other scenario. In contrast, in the WRW scenario there are significant land use shifts towards "unmanaged land" at the expense of both agriculture and forestry which leads to high biodiversity vulnerability due to the species selected within the index.

The index is based on a group of 12 species selected to represent a cross-section of European species from different taxa, regions and habitats, but there is a focus on species associated with arable and forest land uses to highlight the impacts of cross-sectoral influences. Whilst the choice of these species influences the results, it is clear that changes in land use are likely to have significant impacts on species already under threat from climate change. The reduction in vulnerability in northern Europe compared to increases in vulnerability elsewhere reflects many of the selected species gaining climate space in the north for warmer and sometimes wetter scenarios. The north may, therefore, present opportunities for some of the more mobile threatened southern species.

3.2.5 Water-related Indices: Water Exploitation Index and Irrigation Usage

The water exploitation index is the ratio of total freshwater demand divided by total freshwater availability and indicates water stress when the index ≥ 0.4. The climate-only scenarios have a significant impact on patterns of both water exploitation and irrigation. In all cases the high emissions scenarios lead to more extreme values of the water exploitation index (i.e. more water stress), particularly in southern and eastern Europe (Figure 1). The GFCM21 high emissions scenario stands out as a worst-case scenario for the water exploitation index, particularly in the south and east: the 25th and 75th percentiles increase from 0.14 and 0.37 at baseline to 0.58 and 1.22 in the GFCM21_H scenario, far exceeding the 0.4 threshold indicating water stress. Mean difference from baseline in western Europe is mixed, whilst northern Europe has no change in water exploitation in any scenario (Table 1b).

The socio-economic scenarios exacerbate conditions, extending both maximum and minimum values (Table 1b). In general, the utopian scenarios have lower values of the water exploitation index and show higher levels of irrigation, particularly in southern and eastern Europe. Of the two scenarios, Riders uses more irrigation and has higher water exploitation values. Conversely, irrigation usage in SoG and Icarus is low, and only present in the south. Moreover, the water exploitation values are notably higher: in western Europe the 25th percentile of the dystopian scenarios (SoG and Icarus) is greater than the 75th percentiles of the utopian scenarios (WRW and Riders) (Figure 1). These patterns reflect differences in the scenarios, particularly in terms of technological water savings and irrigation efficiency which all increase in the utopian scenarios, but decline in the two dystopian scenarios. "Changes in water efficiency from behavioural change" is also lower in the dystopian scenarios, and negative in Icarus. These factors reflect a division between scenarios: the utopian scenarios, where innovation in terms of water saving, allows greater areas of farmland to be irrigated with less impact on the overall water supply as represented by the lower water exploitation index; and the dystopian scenarios in which pressures on water supply, and the lack of efficient irrigation, mean that irrigation is a less viable option.

Discussion

Impacts across sectoral indicators are more robust, in terms of showing a consistent direction of change, under the climate-only scenarios compared to the combined climate and socio-economic scenarios. Out of the 55 indicator/region combinations (Table 1b), 53 show a consistent direction of impact under the climate-only scenarios which reduces to 32 when socio-economic change is considered. This concurs with previous research that has suggested that non-climatic pressures may be more important than climate change (Holman et al. 2005) and highlights the importance of accounting for socio-economic change and climate change in a co-evolutionary way (Lorenzoni et al. 2000). Adding the socio-economic scenarios to climate change also increases the range of outcomes across Europe, which demonstrates the potential for societal adaptation to reduce the severity of climate change impacts (Jäger et al. this volume).

The study also highlights the importance of taking account of the complex interactions between different sectors under different scenario futures. The response of each sector (indicator) under the various climate and socio-economic scenarios depends on the nature (linear or non-linear), mechanism (direct or indirect), direction and magnitude of the effect of individual drivers on each sector, as discussed in Kebede et al. (this volume), and how these combine as multiple drivers within the scenarios. Drivers that affect sectors in a complex manner, particularly indirect drivers with non-linear effects, are not generally captured in sector-specific studies which can lead to an under- or over-estimation of projected impacts. Alternatively, integrated assessments which take account of cross-sectoral interactions allow appraisal of which sectors “win” or “lose” under different scenario futures. It can be seen from Figure 2 that the sectoral winners and losers vary depending on the socio-economic scenario. In the SoG scenario, the agricultural sector may be categorised as a winner as all indicators related to food production increase significantly; as a result the other land use sectors, such as forestry and unmanaged land, lose land. The water sector may also be considered a loser in SoG as the water exploitation index significantly increases resulting in greater water stress. Conversely, in the WRW scenario, the water sector may be considered a winner, with a decreasing water exploitation index. Urban growth increases under this scenario (hence a sectoral win), but intensive agriculture loses. The loss of arable habitat in WRW means that it shows a greater increase in biodiversity vulnerability than in the other scenarios, however, within the scenario storyline, the increases in unmanaged land are likely to compensate for this, with the eco-conscious WRW population using these areas to support biodiversity impacted by land use change.

Icarus is similar to SoG in that the water sector is a loser as there is greater water stress due to failed innovation. However, intensive farming and food production gain to a lesser extent and there is no urban growth. Furthermore, there is slightly lower biodiversity vulnerability compared to SoG. Icarus is also the only scenario in which there are positive changes (i.e. decreases) in the number of people flooded relative to the levels driven by climate, reflecting the declining population. In the Riders scenario, urban growth increases and food production also increases in many European regions. However, it does not have the dramatic increases in intensive farmland found in SoG. The water sector may also be categorised as a winner in the Riders scenario; irrigation increases in western and eastern Europe without significant negative impacts on the water exploitation index. In contrast to WRW which experiences very dramatic land use change towards unmanaged land, Riders maintains a greater area of agriculture and, thus, maintains a greater landscape diversity leading to less notable increases in biodiversity vulnerability.

This study has assessed impacts resulting from climate and socio-economic scenarios rather than quantifying their contribution to the vulnerability of human well-being. As such, whilst we have identified the winners and losers in terms of sectors, the ability of society to cope with the impacts is not included in this analysis. This is analysed in Dunford et al. (this volume) whose results reinforce the conclusions found here: there are scenarios where vulnerability is less or more in particular sectors, but there is no combination of climate and socio-economic scenario that leads to a position where there is no vulnerability in Europe.

The CLIMSAVE IA Platform is a complex network of interlinked meta-models. It requires careful exploration to identify the relationships between driver variables and output indicators. A key factor in understanding the interactions between sectors in the Platform is recognising the implicit adaptation that occurs within the land use allocation module in prioritising food production. Hence, if it is not possible to meet European food demand with the existing land use distribution, the module autonomously expands agricultural land to meet demand. This means that any driver that has an impact on food demand or agricultural production has a considerable impact on all factors dependant on land use. It also makes scenarios where food provision is de-prioritised, for example, to focus on forest products or biodiversity, harder to replicate within the Platform. Whilst further extensions of the project may re-consider the prioritisation within the land use model the current system still has considerable utility. Firstly, it is still possible, with an understanding of the system, to compensate for the priority given to food within the existing system, for example, through decreasing the proportion of food demand that is not expected to be provided by Europe's land area by increasing "food imports". Secondly, the system does highlight the importance of food security as a key issue driving the future of European land use and the pivotal importance of land use in decision-making across all natural resource sectors. This is highlighted by the projected decreases in forest areas across all scenarios which concur with the results of other land use scenario studies (Rounsevell et al. 2006) that suggest that changes in forest areas largely result from changes in other land uses, such as agriculture.

The quantification of the socio-economic scenarios within the CLIMSAVE IA Platform involved defining a single (default) value, as well as a credible range of values, for each of the socio-economic drivers by stakeholders and project modellers. For example, the default value of population change in WRW is +5%, whilst the credible range varies from -5% to +15%. The scenario analysis reported here focuses on the default values for each socio-economic storyline in an attempt to highlight the key differences between the scenarios. Uncertainty related to the full range of driver values associated with both the socio-economic and climate change scenarios is explored in Brown et al. (this volume). This probabilistic uncertainty assessment found considerable overlap, and hence convergence, across scenarios at the European scale. This is largely consistent with the results presented here in that similar outcomes can arise from different scenario runs. However, the results also show a range of individual indicator responses to the multiple scenarios that are complex and difficult to interpret, and hence understanding why convergent behaviour is observed in practice is elusive.

The scenario analysis undertaken in this study highlights the overwhelming importance of considering cross-sectoral interactions. Figure 2 shows that none of the combined climate and socio-economic scenarios have positive impacts across all sectoral indicators, in all regions of Europe and that situations in which all sectors are winners will be very difficult, if not impossible, to achieve. Adaptation may offer opportunities to reduce and compensate for some of these cross-sectoral impacts as discussed in Jäger et al. (this volume). However, it is clear that the many contrasting demands of the different sectors will pose considerable challenges for managers and decision-makers.

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Climate change integrated assessment methodology for cross-sectoral adaptation and vulnerability in Europe; www.climsave.eu). CLIMSAVE is an endorsed project of the Global Land Project of the IGBP. The authors would like to thank all CLIMSAVE partners for their contributions to many productive discussions related to the content of this paper.

(2) Book Chapters: Abstract

(i) *Mokrech et al. (2015): In: Gray et al. (eds.), Springer Publishing*

Assessing flood impacts, wetland changes and climate change adaptation in Europe: The CLIMSAVE approach

M. Mokrech[1], **A.S. Kebede**[2], R.J. Nicholls[2]

[2] *School of Science and Computer Engineering, University of Houston Clear Lake, 2700 Bay Area Blvd., Box 540, Houston, Texas, United State, Email: Mokrech@uhcl.edu*
[1] *Faculty of Engineering and the Environmental and Tyndall Centre for Climate Change Research, University of Southampton, Highfield, Southampton SO17 1BJ, United Kingdom.*

Abstract

This chapter presents the **C**oastal **F**luvial **Flood** (**CFFlood**) meta-model that has been developed and integrated into a participatory integrated assessment tool to facilitate a two-way interactive process where users can explore flood impacts and adaptation options under a range of climate and socio-economic change scenarios in Europe. The tool enables users to explore socio-economic flood impacts and wetland change/loss due to changes in model parameters within ranges designed through a participatory modelling process to reflect future uncertainty. Changes in flood frequency due to changes in river flows and relative sea level are used to determine the flood extent and depth, which are combined with information on urban landuse, population density and Gross Domestic Product (GDP) to estimate flood impacts. Wetland changes and losses in floodplain are assessed considering three influencing factors of accommodation space, sediment supply, and rate of relative sea-level rise. The benefits of a number of adaptation measures including flood protection upgrades, realignment of flood defences, resilience measures, and mixed responses for reducing flood risks are assessed. Flood impact simulations show that future climate and socio-economic conditions may increase socio-economic impacts, especially coastal flooding due to sea-level rise. In contrast, impacts caused by fluvial flooding may decrease in Southern and parts of Western Europe due to the decrease in precipitation. Incremental losses of coastal wetland habitats (i.e. saltmarsh and intertidal flats) are simulated with the increase of sea-level rise. Under high-end scenarios impacts increase substantially unless there are corresponding adaptation efforts.

(3) Conference Papers: Abstract

(i) *Kebede et al. (2013): ECCA Conference: 18–20 March 2013, Hamburg (Germany)*

Socio-economic and environmental impacts of future changes in flooding and the implications of adaptation in Europe

A.S. Kebede[1], M. Mokrech[2], R.J. Nicholls[1]

[1] *Faculty of Engineering and the Environmental and Tyndall Centre for Climate Change Research, University of Southampton, Highfield, Southampton SO17 1BJ, United Kingdom. Tel. +44 (0) 23 8059 2134, Email: ask2g08@soton.ac.uk*
[2] *School of Science and Computer Engineering, University of Houston Clear Lake, 2700 Bay Area Blvd., Box 540, Houston, Texas, United States*

Abstract

The Coastal Fluvial Flood meta-model (CFFlood) within the CLIMSAVE Integrated Assessment Modelling framework is used to estimate the socio-economic impacts of flooding that are attributed to future changes including socio-economics, climate and sea-level rise in Europe's coastal and fluvial floodplains. The method uses a nested scaling approach to establish credible results that are presented at 10 arc-minute spatial resolution in the Integrated Assessment Platform (IAP). The change in flood frequency due to changes in river flows and relative sea-level rise is used to determine the extent and water depth of flood risk zones. The flood damages (both contents and structure) are calculated using a broad scale approach that accounts for urban areas and people at risk of flooding, flood water depths and Gross Domestic Product (GDP). The effectiveness of a range of adaptation measures including flood protection upgrades, realignment of flood defences, resilience measures, and mixed responses in reducing flood risks are explored.

(4) Official Project Reports

(i) *Kebede et al. (2013): CLIMSAVE Project Report*

Report on identification of key impacts and metrics for cross-sectoral comparison

A.S. Kebede, R. Dunford, P.A. Harrison, *et al*.

Preface

The purpose of this deliverable is to analyse the outputs from the CLIMSAVE Integrated Assessment (IA) Platform to identify those sectors (and their components) which are most exposed and sensitive to climate change, including important cross-sectoral linkages. This is achieved by a combined approach drawing on sensitivity analysis and scenario analysis. In the sensitivity analysis the full range of input variables for the IA Platform are explored whilst the scenario analysis focuses on the climate and socio-economic scenarios selected within the project (see Deliverables 3.4 and 1.1 respectively).

Full report available on:
http://www.climsave.eu/climsave/doc/Report_on_key_impacts_and_cross-sectoral_interactions.pdf

(ii) *Harrison et al. (2013): CLIMSAVE Project Policy Brief for Europe*

Climate Change Impacts, Adaptation and Vulnerability in Europe: An integrated approach

P.A. Harrison and the CLIMSAVE consortium

Full report available on: http://www.climsave.eu/climsave/doc/Policy_Brief_for_Europe.pdf

(iii) *Harrison et al. (2013): CLIMSAVE Project Policy Brief for Scotland*

Climate Change Impacts, Adaptation and Vulnerability in Scotland: An integrated approach

P.A. Harrison and the CLIMSAVE consortium

Full report available on: http://www.climsave.eu/climsave/doc/Policy_Brief_for_Scotland.pdf

(iv) *Gramberger et al. (2012): CLIMSAVE Project Stakeholder Workshop Report*

Report on the second CLIMSAVE European stakeholder workshop

M. Gramberger, K. Kok, M. Maes, B. Stuch, P. Harrison, J. Jagaer, M. Metzger, **A. Kebede**

Full report available on:
http://www.climsave.eu/climsave/doc/Report_on_the_second_European_workshop.pdf

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