The **CLIMSAVE** Project

Climate Change Integrated Assessment Methodology for Cross-Sectoral Adaptation and Vulnerability in Europe

Assessing the robustness of climate adaptation measures in the face of uncertainties

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Preface

The aim of this deliverable is to document the development and use of a methodology for testing the robustness of adaptation policy options. The methodology builds on previous work in the CLIMSAVE Project. The socio-economic scenarios used for testing policy robustness were developed in a stakeholder-led process for both the European and Scottish level and are described in detail in Deliverable 1.4 (Gramberger et al., 2013 a,b) and Deliverable 3.3 (Kok et al., 2013). The test for robustness used in this deliverable is based on the vulnerability indicators developed in Deliverable 5.2 (Dunford et al., 2013). The approach also takes account of the uncertainties inherent in applying the CLIMSAVE Integrated Assessment (IA) Platform, the qualitative and quantitative methods for which are documented in Annex 2 and Annex 3, respectively.

1. Introduction

1.1. Overview of previous research on adaptation policy robustness

There is an increasing amount of research on policy robustness in the area of climate change adaptation, in particular focusing on possibilities for effective, long-term policy responses in the face of uncertainties about future climate change, technological advances and the socio-economic development (see, for example, Lempert and Schlesinger (2000), Dessai and Hulme (2007), Hermeling at al. (2013) and Watkiss and Hunt (2012)).

Adger et al. (2005) claim that successful adaptation policies have the characteristics of being effective, efficient and legitimate, and address equity. Assessing policy robustness in the face of multiple uncertainties is a way to address the effectiveness dimension of adaptation options (Dessai and Hulme, 2007). Deep uncertainty in climate and socio-economic models is characterised by the fact that neither outcomes nor their probabilities are known (also known as fundamental, radical or severe uncertainty, ignorance, black swans, unknown unknowns) and that uncertainty remains unaffected by higher levels of information or analysis since it relies on emergent features of the system (aleatory uncertainty) (Twomey, 2012).

Hence, originally starting from a more traditional approach relying on one predictable future, policy strategies in climate change adaptation have moved from seeking optimisation under determined parameters to a more general “reduction in fragility and towards greater robustness” (Wharton, 2011). A robust policy has “the ability to perform reasonably well under a wide range of possible futures” (Twomey, 2012: 9) and thus rejects the idea of optimisation. To develop robust policies a range of available options and their associated sensitivities to uncertain parameters are considered in order to provide a background for reasonable decisions (Twomey, 2012).

Lempert and Schlesinger (2000) argue that it is important to ask the right questions, if robust policies are searched for. “(…) “what actions should we take, given that we cannot predict the future course of climate change nor the effort that may be required to prevent it?” The answer is that society should seek strategies that are robust against a wide range of plausible climate change futures. By definition, a robust strategy is insensitive to our uncertainty about the future." (p. 6). The authors admit that they are not sure whether such strategies even exist and whether it is possible to find and assess them. What they do state as being clear is that a robust response should employ a set of different types of actions.

Along with conceptual discussions on policy robustness and uncertainties, different methodological approaches have been developed that attempt to quantify robust policy options and inform decision-makers about the outcomes.

Dessai and Hulme (2007) present a methodological framework which evaluates the robustness of different adaptation options, which they applied to water resource planning in the East of England. Their goal was to develop a methodology that quantifies as much uncertainty as possible. They compiled a list of adaptation options and assessed their sensitivity by linking them to uncertainties regarding changes in climate variables (e.g. greenhouse gas emissions) and their impacts (e.g. on the availability of water). As their case study was on the regional scale, one crucial step was to link large-scale climate models with the demand of regional scale water resource planning. They used a sequential modelling approach which examines each parameter separately. Dessai and Hulme (2007) emphasise that the strength of their quite simple and linear approach is – in contrast to complex GCMs – the possibility to perform a sensitivity analysis. On the other hand, its simplicity does not account for the variability and complexity of adaptation options, which is a central aspect to "real-life" decision-making.

In a recent paper by Hermeling et al. (2013), the trade-off between the complexity of policy evaluation and the demand for simple testing methods has been addressed. They developed a methodology that reduces the computations compared to standard sensitivity analyses (an adapted version of the Gauss-quadrature approach) and applied them to the field of climate mitigation policies in the EU. More specifically, Hermeling et al. (2013) performed a multi-dimensional stochastic sensitivity analysis on the results of a simulation model (PACE simulation model, see also Böhringer et al. 2009) that evaluated the impacts of CO_2 emission targets, targets for renewables and energy efficiency on various sectors and regions. While their study focuses on robustness analysis by exploring the effects of different elasticities on sectoral production in the PACE model, they see it as a promising approach for future extension into other areas of computational economics.

In the field of climate adaptation, Watkiss and Hunt (2012) criticise the fact that economic literature primarily focuses on costs and benefits (cost-benefit analysis, cost-effectiveness analysis or multi-criteria analysis) of adaptation options, which are assessed for one defined scenario at a time and do not recognise uncertainties. Thus, new decision support tools are emerging and their paper analyses three of them: Real Option Analysis, robust decision-making and portfolio analysis. These tools were developed in several FP7 projects, where the authors were involved, and their aim was to look into them and test them practically. Robust decision-making, for instance, is used in situations with strong uncertainty where hardly any probabilistic information is available. It defines a strategy as robust if it performs reasonably well over a wide range of scenarios. Portfolio analysis does not choose one strategy, but helps to select a set of options that are effective together over a range of possible projected future climates. The strength of choosing more than one option is emphasised here. All three approaches are technically complex (not possible to download), thus not easy to apply and work well for specific applications.

1.2. Objectives of this paper

The overall aim of this work in the CLIMSAVE project was to examine whether adaptation responses are "robust", by looking at whether they would reduce vulnerability to climate and socio-economic changes across sectors, scales and scenarios.

To assess the robustness of adaptation options, the following steps were required and are described in this paper:

(i) First, it was necessary to cluster the adaptation options that can be tested using the CLIMSAVE IA Platform, since the objective was not to test the performance of individual measures but to test broader policy strategies. The clusters, called policy archetypes, are described in Section 2.1.
(ii) Second, the IA Platform was run assuming "no adaptation" for the 2050s timeslice for the four CLIMSAVE socio-economic scenarios developed for Scotland and Europe and for two climate scenarios. Results were analysed for four of the vulnerability sectors (i.e. biodiversity, flooding, water exploitation and food provision) that can be explored using the CLIMSAVE IA Platform, as described in Section 2.2.
(iii) Third, the IA Platform was run for the clusters of adaptation options associated with each of the four policy archetypes for the same scenarios and vulnerability sectors.
(iv) Finally, for each of the runs the number of vulnerable people was calculated.

The results can be analysed (Section 3) using the following questions:

- Do each of the policy archetypes reduce vulnerability at both the Scottish and European levels?
- Do the policy archetypes reduce vulnerability in all socio-economic scenarios?
- Do the policy archetypes reduce vulnerability in both climate scenarios?
- For any socio-economic scenario combined with a selected climate scenario, do the policy archetypes reduce vulnerability in all sectors?

In addition to the adaptation options covered by the CLIMSAVE IA Platform there are other so-called "soft options". Section 3.2 shows the results of a qualitative assessment of the robustness of these options.

Applications of the CLIMSAVE IA Platform involve a number of inherent uncertainties arising from the underlying data, the goodness of fit of the meta-models to their underlying process model and from the propagation of errors through the chain of coupled meta-models. A qualitative and quantitative uncertainty analysis was undertaken with the Platform in order to rank the vulnerability indicators used here in terms of their relative uncertainty. This provides further evidence in support of the robust policy assessment. The approach is described in Section 4.

Finally, Section 5 reflects on the results of this study of policy robustness with a focus on the usefulness of the approach taken and some trends observable in the results.

2. Method

The CLIMSAVE approach to assessing the robustness of policies makes use of the IA Platform as well as expert judgment, as described below. For this analysis a robust policy measure was defined as one which has benefits across sectors, scenarios and spatial scales. A benefit is an improvement in human well-being through a reduction of vulnerability to climatic and socio-economic change.

2.1. Policy archetypes

It is not possible to test the effects of policies within the CLIMSAVE IA Platform, but rather to test adaptation options. Therefore, for the robustness analysis the adaptation options available on the IA Platform were clustered into so-called "policy archetypes". Four archetypes were defined as briefly described in Box 1 and then described in more detail in the rest of this section.

Box 1: Policy archetypes used in the robustness analysis

Ecosystem-based Adaptation (EbA) The goal of EbA is to protect or improve to the integrity and health of ecosystems and habitats so that nature retains capacity for adapting to changing complex pressures and conditions, such as climate change.

Market-based Adaptation (MbA) The major objectives of market-based adaptation (MbA) are fund raising/mobilisation for adaptation activities; efficient allocation of funds that are available for projects aiming to avoid climate change related damages; promotion of adaptation by various stakeholders; and sharing of financial risks in the context of climate change (e.g. transfer of risks through insurance-based mechanisms).

Technology-based Adaptation (TbA) The goal of TbA is to adapt to climate change and variability through the use of technology such as irrigation, flood defences and advanced early warning systems.

People-based Adaptation (PbA) The goal of PbA is to adapt to climate change and variability using human and social capital. This includes education and awareness-raising, building of networks to respond to climate change and changing institutions (including regulation).

2.1.1 Ecosystem-based Adaptation (EbA) policy archetype

Goals of the policy

As the EU Ad-Hoc Expert Working Group on Biodiversity and Climate Change (2009: 5) has put it: "An increasing number of recent reviews, policy documents and reports e.g. "The Natural Fix? – the role of ecosystems in climate mitigation" by UNEP and "Convenient Solutions to an Inconvenient Truth: Ecosystem-based Approaches to Climate Change" by the Environment Department of The World Bank emphasise the two-way link between biodiversity and climate change and demonstrate an increasing awareness of the important role of ecosystems in the climate system as well as of the value of protecting biodiversity as a route to moderating climate change."

Nature conservation and biodiversity policy has a traditional role to protect the integrity of ecosystems and the diversity of habitats, as well as species and genetic diversity (biodiversity at different scales). An effective nature conservation and biodiversity policy contributes to realising the objectives of maintaining the integrity and health of ecosystems and habitats; that means protecting the stability, resilience, and diversity of natural systems. By implication, nature retains her capacity for adapting to changing complex pressures and conditions, such as climate change. Natural systems, if not degraded or impaired, have the capacity of, and can provide human communities with, autonomous adaptation. Often used **policy instruments** (practices and tools) of nature conservation and biodiversity policy that contribute to the capacity for autonomous adaptation include (among others):

- Ecological corridors that establish connectivity between habitats (see, e.g., the Pan-European Ecological Network)[1];
- Ecological restoration (re-establishing ecological health and integrity) to assist in species movement in response to climate change, and as a means of building larger, resilient species populations and habitats.

New practices and tools might cover:

- Supporting the conservation of agro-biodiversity by supporting on-farm conservation initiatives;
- Innovative funding schemes, such as payment for ecosystem services (PES); and
- Investing in green infrastructure (e.g. green roofs, urban/peri-urban agriculture, green urban space, etc.).

These constitute, therefore, a cost-efficient way of climate adaptation: healthy natural systems provide their services to human communities free of charge (see Table 1). Therefore, EbA identifies and implements a range of policy instruments for the management, conservation and restoration of ecosystems to provide services that enable people to adapt to the impacts of climate change. In this sense, EbA explicitly demonstrates the role ecosystem services could play in adaptation to climate change (Vignola et al., 2009).[2]

It is claimed that EbA offers triple-win measures – those that (i) protect and restore ecosystems (increase in *Natural Capital*), (ii) contribute to mitigation by reducing emissions, and (iii) constitute a cost-effective way of adapting to the impacts of climate change (increase in *Financial Capital*). In addition, ecosystem-based adaption options are argued to be more accessible to rural and poor communities thus promising to enhance social justice and equity (increase in *Social Capital*). With this win-win-win mind-set, EbA aspires to be a route to a robust and sustainable climate change adaptation policy.

[1] Land-use and spatial planning can, for example by countering fragmentation and isolation, contribute to improving the ecological coherence of the Natura 2000 network Europe-wide.

[2] "We define ecosystem-based adaptation as the adaptation policies and measures that take into account the role of ecosystem services in reducing the vulnerability of society to climate change, in a multi-sectoral and multi-scale approach. EbA involves national and regional governments, local communities, private companies and NGOs in addressing the different pressures on ecosystem services, including land use change and climate change, and managing ecosystems to increase the resilience of people and economic sectors to climate change." (Vignola et al., 2009: 692)

Table 1: Some examples for EbA (*Source: EU Ad Hoc Expert Working Group on Biodiversity and Climate Change, 2009: 18-19).*

EbA	**Expected benefits**
Maintain and restore floodplains, forests, wetlands and peatland	Adaptation, mitigation, nature conservation, flood protection, water purification
Use soft coastal defences, maintain and restore mangroves and other coastal forest; protect coral reefs	Adaptation, mitigation, nature conservation, coastal protection, fishing nursery leading to revitalised fish stocks thus improving livelihoods
Maintain and restore vegetation cover, e.g. diverse mountain forest, grasslands	Adaptation, mitigation, nature conservation, erosion and landslide protection, water storage and purification
Increase green spaces in cities; planting trees and installing vegetal roofs	Adaptation, mitigation, cooling, filtering of the air, provision of habitat, stepping stones, improved quality of life
Use diverse crops in agriculture, improve input management, preserve high quality soils for agriculture	Adaptation, enhanced food security, increased agricultural biodiversity, increased soil quality, improved water storage and purification
Diversify forest stands and conserve old growth forest	Adaptation, nature conservation, storm protection, water storage and purification

Policy mechanism

It is argued that EbA is applicable by any sector affected by climate change. If other policy sectors take into consideration the potential services nature provides and build their policies accordingly climate policy integration (CPI) will be an evident implication. CPI may indeed be inevitable due to the fact that:

"[c]limate change does not act in isolation. It interacts with and often exacerbates other existing pressures such as pollution, over-exploitation, invasive species, habitat fragmentation by changes in land use, and habitat degradation and loss." (EU Ad Hoc Expert Working Group on Biodiversity and Climate Change, 2009: 15).

Thus, mainstreaming climate change into other sectoral policies, by linking ecosystems and other sectors in adaptation, may constitute a powerful **policy mechanism**. For example, in the case of spatial planning, Wilson and Piper (2008) argue that:

"…in circumstances of climate change, spatial planning has a particularly important duty to put in place measures that directly protect and enhance biodiversity, and measures that control the impacts of human activities, or safeguard areas of current or future importance for biodiversity. Many of these measures will also provide other benefits both for the support of ecosystem functions and for human quality of life." (Wilson and Piper, 2008: 147).

One may clearly draw guidelines from healthy and resilient ecosystems to climate-proof sectoral policies. In this sense, it is recommended to merge climate-proofing and biodiversity-proofing of sectoral policies since they are the two sides of the same coin. EbA may thus be considered as an insurance policy against irreversible damage resulting from extreme weather events in particular and climate change in general.

Establishing science-policy-society interfaces could be another significant **policy mechanism** within EbA. An institutionalised dialogue holds the promise for unleashing creative and context-specific (i.e. feasible) adaptation alternatives within the multi-level and multi-scale governance structure characterising climate change policy.

Concrete policy measures

The EbA adaptation measures that were suggested by the stakeholders in the European and Scottish workshops are shown in Table 2.

Table 2: EbA adaptation measures suggested by stakeholders.

Sector	**Measures**
Water	Rain-water harvesting rather than big systems
Forests	Lower intensity forest management
Agriculture	Storm and drought resistant crops Low input, sustainable agriculture, permaculture
Flooding	Wetland creation by moving flood defences inland Discouraging coastal development to reduce exposure to flooding
Landscape	Urban agriculture Trees and plants in cities; Increase green space in cities Spatial planning policies to control urban expansion Multi-use landscape Land use management to optimise resources and improve ecosystem services
Biodiversity	Green roofs as local solution Protecting biodiversity outside protected areas Enlarge existing protected areas Increase number of protected areas Improve connectivity of nature reserves

2.1.2 Market-based Adaptation (MbA) policy archetype

Goals of the policy

The key feature of market mechanisms is that a **price signal** is used to promote the production of a certain service or good, or to reduce it (Stavins, 2003). The major objectives of market-based adaptation (MbA) are:

- Fund raising/mobilisation for adaptation activities;
- Efficient allocation of funds that are available for projects aiming to avoid climate change related damages;
- Promotion of adaptation by various stakeholders; and
- Sharing of financial risks in the context of climate change (e.g. transfer of risks through insurance-based mechanisms) (Butzengeiger-Geyer et al., 2011).

Market-based instruments are better known for climate change mitigation. Initially used to provide incentives for reducing pollution, market mechanisms include the trading of quotas, as well as the use of taxes and subsidies. For adaptation, Callaway (2004) proposed a system of adaptation credits "to narrow the difference between marginal benefits and marginal costs", but did not elaborate on it. A trading system for adaptation could also be specified in a way that it limits "risky activities", and thus would be similar to the permit trading systems for classical pollutants (Kuch and Gigli, 2007). In this case, activities that are likely to be strongly affected by climate change would be capped. Anyone wanting to engage in such an activity would have to acquire an allowance. The price to be paid for the allowance would be designed to deter people from engaging in the risky activity.

Where adaptation is linked to the reduction of resource use, market mechanisms have already been applied, e.g. in the case of tradable water access rights (e.g. Cantin et al., 2005; Grafton, 2005; Luo et al., 2003).

Agrawala and Fankhauser (2008) distinguish the following instrument categories relevant for key sectors:

- Insurance schemes (all sectors; extreme events);
- Price signals / markets (water; ecosystems);
- Financing schemes via Public-Private-Partnerships or private finance (flood defence, coastal zones, water);
- Regulatory measures and incentives (infrastructure: building standards; zone planning); and
- Research and development incentives (agriculture, health).

Butzengeiger-Geyer et al. (2011) categories the market-based adaptation instruments as follows:

- Subsidies: Direct payments and grants (competitive tendering or payment per unit); Tax reductions; Price supports.
- Taxes and fees: Taxes to raise adaptation funds; Taxes to limit resource use.
- Tradable quotas: Adaptation Market Mechanism: obligation for entities to achieve adaptation units; Tradability of quotas.
- Project offsets: Domestic offsets; International offsets.
- Related market mechanisms: Payments for ecosystem services; Water markets; Habitat banking.

Concrete policy measures

The MbA adaptation measures that were suggested by the stakeholders in the European and Scottish workshops are shown in Table 3.

Table 3: MbA adaptation measures suggested by the stakeholders.

Sector	Measures
Water	Subsidies for innovators Tax/incentives to accelerate transformation to green economy Insurance on climate change risks for all sectors Compensation payment schemes Hydro public-private partnership: water storage + electricity
Forests	Subsidies for innovators Tax/incentives to accelerate transformation to green economy Insurance on climate change risks for all sectors Compensation payment schemes
Agriculture	Subsidies for innovators Taxing calories Crop insurance for heat waves Promoting local food Tax on food waste Insurance on climate change risks for all sectors Compensation payment schemes Public-private initiatives in agriculture Weather derivatives
Flooding	New insurance for extreme events Insurance pool at EU level for natural disasters Insurance on climate change risks for all sectors Compensation payment schemes
Landscape	Tax/incentives to accelerate transformation to green economy Insurance on climate change risks for all sectors Compensation payment schemes
Biodiversity	Tax/incentives to accelerate transformation to green economy Insurance on climate change risks for all sectors Compensation payment schemes

2.1.3 Technology-based Adaptation (TbA) policy archetype

Goals of the policy

The goal of TbA is to adapt to climate change and variability through the use of technology such as irrigation, flood defences and advanced early warning systems. As the web-portal WeAdapt points out, there are no significant technical or legal barriers to increasing the availability and use of technologies for adaptation to climate change. Whereas for climate change mitigation, intellectual property rights have been a barrier to implementation, this is not generally the case for adaptation. The application of environmentally sound technologies (ESTs) in the field of adaptation to climate change is therefore increasingly being realised and explored (http://weadapt.org/knowledge-base/using-climate-information/technology-for-adaptation).

Technology-based policies are better known in the area of pollution reduction, where they are most often referred to as "command and control" regulations. Governments have usually employed command and control regulations to introduce the "best available control technology" that industry should use to control pollution. Technology-based standards typically require the use of specified equipment, processes, or procedures. In the context of climate change mitigation policy, these could be requirements for particular types of energy efficient motors, combustion processes, or landfill gas collection technologies. Many authors have noted that technology and performance standards can be effective in achieving established environmental goals and standards, but they tend to lead to non-cost-effective outcomes in which firms use unduly expensive means to control pollution (e.g. Tietenberg, 1985; Dudek et al., 1992). A technology-based approach is insensitive to the costs and benefits of installing particular technologies at different sites, which makes it much less useful for climate change adaptation. It has also been argued that technology standards discourage innovation (Dudek et al., 1992), because if a technology is designated as "best" and the adoption of this technology is mandated, then it captures the market and forces out other technologies. Furthermore, technology-based regulations have been shown to require a large government bureaucracy to study industries and choose technologies. Funding such a centralised approach is expensive.

Concrete policy measures

The TbA adaptation measures that were suggested by the stakeholders in the European and Scottish workshops are shown in Table 4.

Table 4: TbA adaptation measures suggested by stakeholders.

Sector	Measures
Generic	Early warning systems
Water	Improve irrigation efficiency Efficient irrigation systems Reduce water demand by using technology Large infrastructure for water distribution Large storage system for water Water supply - water storage desalination Rainwater, greywater systems for buildings Develop water export facilities Switch to waterless sewage system
Agriculture	Agriculture: genetic technology, irrigation, wind protection Genetic technology for resilient varieties
Flooding	Improve flood defences by upgrading the standard Take measures to diminish flood damages Walls for flood protection Floating houses
Landscape	Cheap concrete house production Quick-built infrastructure Build artificial winter sport centres Green cities Coordinated transport modes to facilitate public transport Adapt urban fabric (building, infrastructure)
Biodiversity	Green infrastructure

2.1.4 People-based Adaptation (PbA) policy archetype

Goals of the policy

The goal of PbA is to adapt to climate change and variability using human and social capital. These have been defined in Deliverable 4.1 (Tinch et al., 2012) in the CLIMSAVE project as:

Human capital goes beyond simple conceptions of the labour force and includes health, knowledge, skills and motivation.

Social capital consists of the structures, institutions, networks and relationships that enable individuals to maintain and develop their human capital in partnership with others, and to be more productive when working together than in isolation. It includes families, communities, businesses, trade unions, voluntary organisations, legal/political systems and educational and health institutions.

A wide range of policy instruments can be used to increase/improve human capital, including support for improving the education system, health system and job training through tax and subsidy programmes.

The importance of social capital in adaptation to climate change has received considerable attention in recent years (Adger, 2003; Pelling and High, 2005; Wolf et al., 2010; Woolcock and Narayan, 2000). It is recognised that the ability to adapt to climate change depends in part on networks and relationships within society. In particular for the poor, one of the main means of protection against risk is the use of social connections, including the extended family.

This recognition of the importance of social capital (and to some extent, human capital) has led to the increasing implementation of "Community-based adaptation" to climate change (Reid et al., 2009), which focuses on empowering communities to use their own knowledge and decision-making processes to take action[3][4][5]. This approach is participatory and builds on the priorities, knowledge and capacities of local people.

People-based policy has been central in dealing with poverty and unemployment. Poverty in turn is a significant factor determining the vulnerability of individuals and societal groups to climate change. The range of policy approaches (see, for example, Spencer, 2002) to deal with poverty and unemployment includes: transportation vouchers, housing vouchers, and other sorts of direct transfers of valued assets to individuals through, for instance, welfare payments. Subsidies for local public employment, support for parental involvement in a child's education and job creation programmes are further policy approaches.

A focus on "people" has also led to a shift in policy mechanism in some places. One example is that of Wales (Quinn, 2002), where there was a documented shift from "evidence-based" policy-making to "people-based" policy-making through the introduction of participatory

[3] http://www.iied.org/empowering-communities-adapt-climate-change

[4] http://sgp.undp.org/index.php?option=com_areaofwork&view=summary&Itemid=177#.UVg6pjfjBls

[5] http://www.careclimatechange.org/tk/cba/en/

processes that engage both those who are meant to be influenced by policy changes and those who may have to implement them.

Concrete policy measures

The PbA adaptation measures that were suggested by the stakeholders in the European and Scottish workshops are shown in Table 5.

Table 5: PbA adaptation measures suggested by stakeholders.

Sector	**Measures**
Water	Reduce water use by promoting a behavioural change Saving water projects in kindergarten EU water expert centre Early warning
Forests	Community woodlands
Agriculture	Reduce meat consumption Local food supply Vegetarian push with some livestock for soil fertility Dietary education Reduce food waste Menus in restaurants to be 80% vegetarian Early warning More "green" food labels, different approach for agriculture Community allotments
Flooding	Religious neighbourhood provides help in crises (heat waves, floods) EU coastal expert centre Early warning Bring back flags: flood liaison + advice groups
Landscape	Increase green space in cities Coordinated transport modes to facilitate public transport Effective information systems to reduce transport
Biodiversity	Tax/incentives to accelerate transformation to green economy Volunteering projects

2.1.5 Implementing the policy archetypes in the CLIMSAVE IA Platform

To test the adaptation options using IA Platform, the options were grouped according to the policy archetypes. Table 6 shows the clustering of the adaptation options in each archetype. Some options are included in more than one archetype. So, for example, water demand prioritisation is included in both the EbA and the MbA archetypes. For the EbA archetype, the environment was set as the priority sector for water to maintain minimum environmental flows, while for MbA the priority was set to domestic/industrial uses. The flood risk adaptation approach was set to “Retreat” for EbA, “Mixed” for MbA, “Upgrade” for TbA and “Resilience” for PbA. The reasoning behind these choices is that “Retreat” opens space for ecosystems, “Upgrade” is clearly a technological approach of building infrastructure, “Resilience” satisfies the needs of people for a safe environment, while “Mixed” is open to the use of market mechanisms. For each policy archetype, the slider for each adaptation option was changed to the maximum amount that was credible for each socio-economic scenario. The tests were all carried out for the 2050 timeslice. Full details of the adaptation options for all policy archetypes and all European and Scottish scenarios are listed in Annex 1 along with the slider settings used for testing each option within an archetype.

Table 6: Clustered adaptation options of each policy archetype.

EbA **Adaptation options in IA Platform**	**MbA** **Adaptation options in IA Platform**	**TbA** **Adaptation options in IA Platform**	**PbA** **Adaptation options in IA Platform**
Water demand prioritisation to the environment	Water demand prioritisation for domestic/industrial use	Water savings due to technological change	Water savings due to behavioural change
Reduce diffuse source pollution from agriculture	Increase food imports	Reduce diffuse source pollution from agriculture	Reduce dietary preferences for beef and lamb
Protected Area (PA) changed by increasing the number of PAs to improve connectivity and by increasing the size of existing PAs		Improvements in irrigation efficiency	Reduce in dietary preference for chicken and pork
Increasing the amount of Protected Area allocated to forest and agriculture land uses		Improvements in agricultural yields	Increase social capital
Increase compact development		Improvements in agricultural mechanisation	Increase human capital
Flood risk management adaptation approach: Retreat	Flood risk management adaptation approach: Mixed	Flood risk management adaptation approach: Upgrade	Flood risk management adaptation approach: Resilience
Increase in bioenergy production	Forest management for 5 tree species: Even-aged	Forest management for 5 tree species: Optimum	Forest management for 5 tree species: Uneven-aged
		Increase manufactured capital	

2.2 Testing using the IA Platform

As noted above, the test of the archetypes was based on calculating **the number of vulnerable people.** The methodology for calculating this number is described in detail in Deliverable 5.2 (Dunford et al., 2013).

The archetypes were tested for all socio-economic scenarios in Scotland and Europe (see Figure 1). These scenarios are described in detail in Deliverable 1.4 (Gramberger et al., 2013a, b) and described briefly in Box 2.

Box 2: Short description of the European and Scottish socio-economic scenarios

European Scenarios

The most prosperous future scenario, combining high levels of innovation and gradual economic development is ***We are the World***, 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. In comparison, 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*** 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. In this scenario most citizens live in an insecure and unstable world. The ***Riders on the Storm*** scenario is equally hit hard by continual economic crises. However, actors successfully counter the situation through investment in renewable energies and green technologies. In this scenario Europe is an important player in a turbulent world.

Scottish scenarios

Within the ***Tartan Spring*** scenario a far-reaching, poorly regulated privatisation, changes Scotland from a prosperous country with abundant resources to one with an eroded social fabric and a low standard of living, culminating in an uprising. Equally driven by crises, a new self-centred paradigm emerges in the ***Mad Max*** scenario, which leads to a growing disparity in society. Survival from day to day prevails, while new 'clans' are ruling Scotland again. Although resources within ***The Scottish Play*** scenario are equally scarce, the scenario can rely on traditional Scottish values to deal with the lack of resources. Consequently, lifestyles change towards reducing, reusing and recycling, leading to a poorer, but greener and, in a way, happier population. In the most fortunate scenario, ***Mactopia***, a resource surplus helps Scotland to make a transition towards an equitable and sustainable society to eventually become an IT, life sciences, green technology and finance frontrunner led by a powerful middle class.

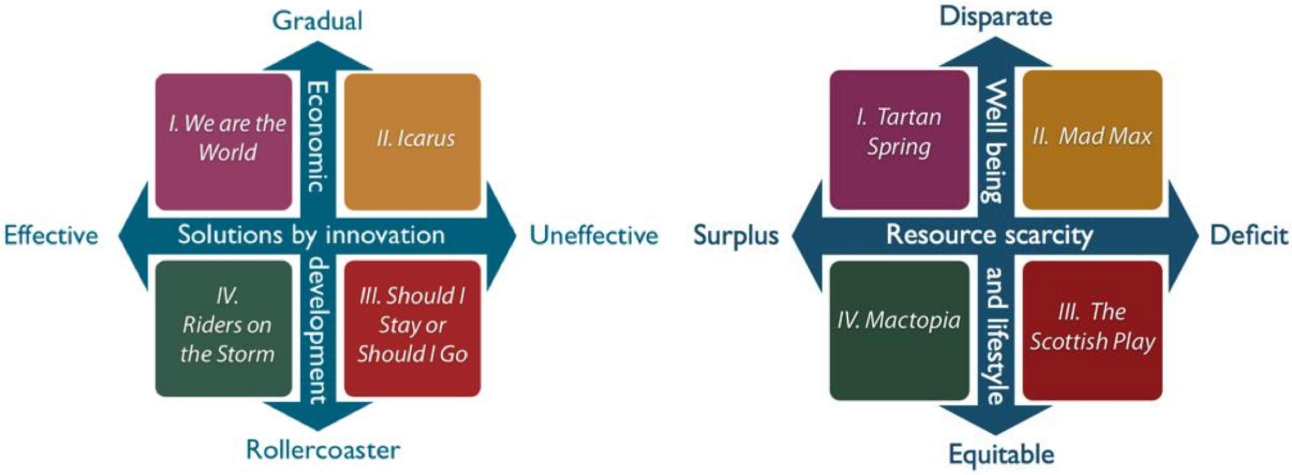

Figure 1: Framework for the European (left) and Scottish (right) socio-economic scenarios (Source: Deliverable 1.4; Gramberger et al., 2013a,b).

The policies were tested using two climate scenarios available on the CLIMSAVE IA Platform. The first scenario is from the GFCM21 climate model using the A1 greenhouse gas emissions and high climate sensitivity. The annual precipitation and temperature relative to baseline are shown in Figures 2 and 3. The second climate scenario is from the IPCM4 climate model using the B1 greenhouse gas emissions and low climate sensitivity. The annual precipitation and temperature relative to baseline are shown in Figures 4 and 5. These two climate scenarios are referred to as C1 and C2 in the analysis of the results. The C1 (GFCM21) scenario is a warm and dry scenario, with temperature increases of up to 4°C in southern Europe and precipitation increases only in northern Europe. The C2 (IPCM4) scenario is a cooler and wetter scenario with temperature increases nowhere above 2°C and precipitation increases over a much larger area of Europe than seen in the C1 scenario.

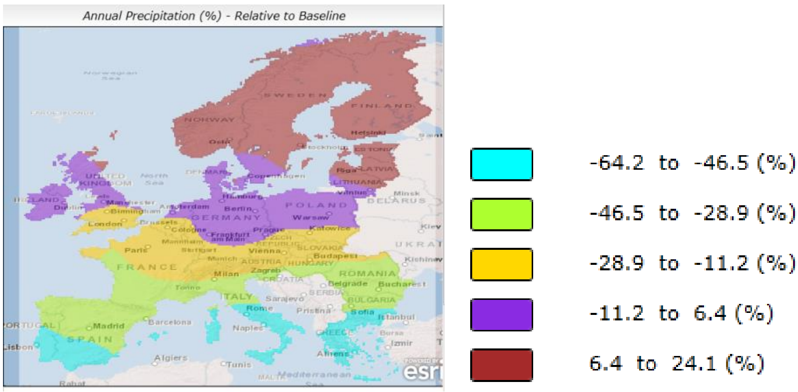

Figure 2: Annual precipitation change in the 2050s relative to the baseline for the GFCM21 climate model combined with an A1 emissions scenario and high climate sensitivity. This scenario is referred to as C1 in the results tables.

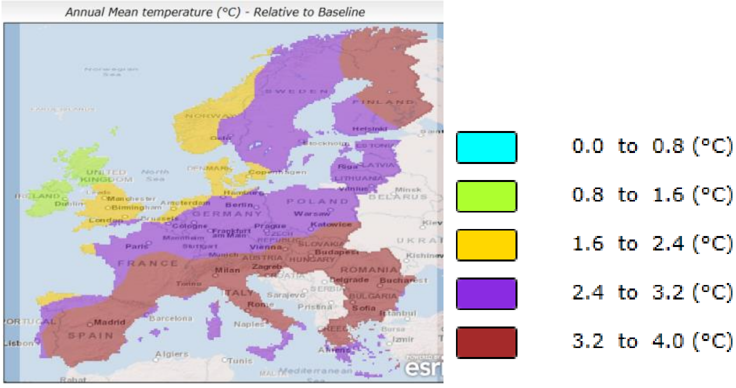

Figure 3: Annual temperature change in the 2050s relative to the baseline for the GFCM21 climate model combined with an A1 emissions scenario and high climate sensitivity. This scenario is referred to as C1 in the results tables.

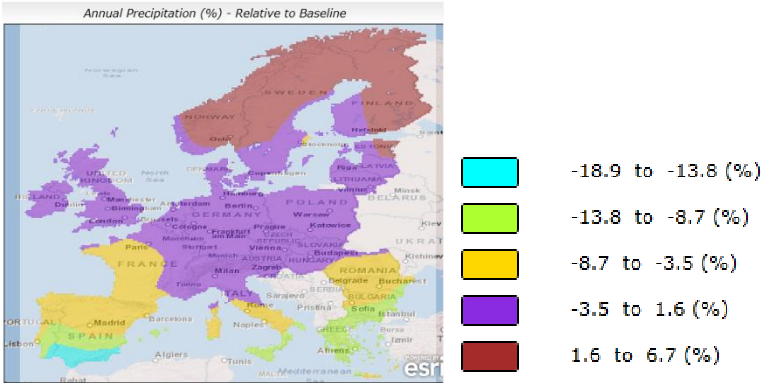

Figure 4: Annual precipitation change in the 2050s relative to baseline for the IPCM4 climate model combined with a B1 emissions scenario and low climate sensitivity. This scenario is referred to as C2 in the results tables.

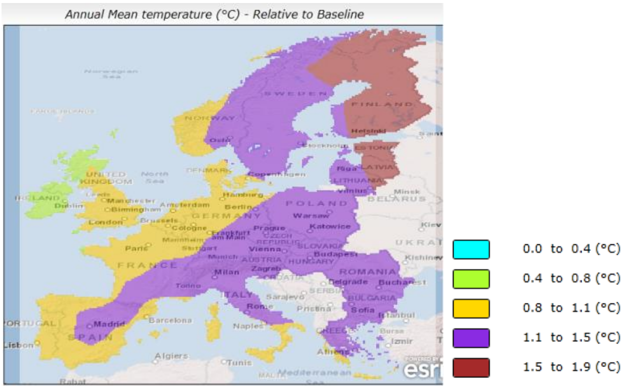

Figure 5: Annual temperature change in the 2050s relative to baseline for the IPCM4 climate model combined with a B1 emissions scenario and low climate sensitivity. This scenario is referred to as C2 in the results tables.

For the Scottish runs, the UKCP09 climate scenarios were used (see Deliverable D7.3b; Harrison et al., 2013). Two scenarios were tested: one in which Scotland is relatively hot and dry in the 2050s (achieved by combining a high emissions scenario with setting the annual temperature change to the 90th percentile and the summer and winter half-year precipitation to the 10th percentile, as indicated in Figure 6); and one in which Scotland is relatively cool and wet in the 2050s (achieved by combining a low emissions scenario with setting the annual temperature to the 10th percentile and the summer and winter half-year precipitation to the 90th percentile, as indicated in Figure 7).

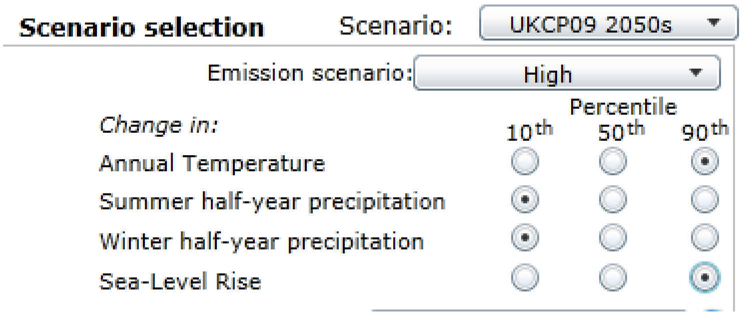

Figure 6: Settings used in the Scottish IA Platform for a hot-dry climate scenario.

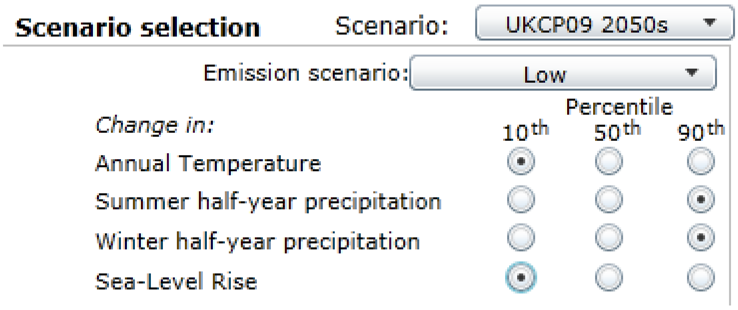

Figure 7: Settings used in the Scottish IA Platform for a cool-wet climate scenario.

By testing the policy archetypes for both Scotland and Europe using the two versions of CLIMSAVE IA Platform it is possible to assess whether they are effective at these two scales.

The tests have been carried out for four of the vulnerability sectors in the CLIMSAVE IA Platform: food provision, water exploitation, flood, and biodiversity.

2.3 Testing "soft options" not included in the IA Platform

There are many "soft" adaptation options that are not included in the IA Platform, so these were incorporated into the assessment of policy robustness using expert judgement. The options were sorted according to policy archetype. For example, education belongs to the PbA archetype, while insurance schemes belong to the MbA archetype. A qualitative assessment was then made of the effectiveness of the resulting clusters.

Table 7: Clustering of “soft options”.

Options	Comments/Examples
PEOPLE-BASED ADAPTATION	
Education Awareness raising	Promotion of healthy lifestyles Promotion of environmental choices Education/information for new technology Support/extension Labelling schemes
Early warning systems	Weather forecasting systems Flood warning Systems
Saving water projects in kindergarten, school	
Home grown foods	
Regulation on NPK, pesticides	
Planning restrictions on greenfield developments	
HORECA menus meet statutory vegetarian targets	
Minimum density requirements for new housing developments	
Planning controls on development within coastal floodplain	
Making people move out of flood prone areas	
Emergency procedures/stocks	For flooding, drought, etc.
Hosepipe bans	
Regulate minimum standards for new technology	
Ban/restriction on GMO lifted	
Trade policy to restrict imports	
Domestic policy to encourage/discourage production	
Regulation on NPK, pesticides	
Planning restrictions on greenfield developments	
MARKET-BASED ADAPTATION	
Direct pricing policy	Via tax on meat
Changes to agricultural support payments	Changes to agricultural subsidies
Indirect pricing policy	Via tax on animal emissions
Water pricing	
State/EU subsidy for scaling up new technology	
Subsidise return to low mechanisation	
Tax on polluting imports	
Subsidise imports	
Reducing subsidies for bioenergy	
Taxes on biofuels	
Nitrogen tax, pesticide tax	
Forest subsidies	
Tax on empty properties	
Tax on second homes	
Tax breaks or regulatory relaxation on letting parts of properties	
Availability of flood insurance	

3. Results

3.1 Testing the archetypes using the IA Platform

Tables 8 and 9 show the results of testing the four policy archetypes for the individual vulnerability sectors, for the four socio-economic scenarios and two climate scenarios in Europe (Table 8) and Scotland (Table 9). White cells indicate that the number of vulnerable people is the same as with no adaptation. Green cells show where the policy archetype reduces vulnerability. Red cells show where vulnerability increases.

Table 8: Results for Europe (thousands of people vulnerable) for four vulnerability sectors, four socio-economic scenarios (We are the World (WATW), Icarus, Riders on the Storm (Riders) and Should I stay or Should I go (Should I stay)) and two climate scenarios (C1 = GFCM21-A1 emissions-high sensitivity; C2 = IPCM4-B1 emissions-low sensitivity).

	Biodiversity							
Socio-economic scenario	WATW		ICARUS		Riders		Should I stay	
Climate scenario	C1	C2	C1	C2	C1	C2	C1	C2
No Adaptation	**1121**	**467**	**2018**	**890**	**631**	**121**	**2388**	**1005**
EbA	1107	414	1980	935	614	120	2386	1002
MbA	1236	443	2055	1008	641	158	2387	1011
TbA	1052	448	2027	1060	613	200	2375	842
PbA	824	438	1737	755	544	145	1970	727

	Water exploitation index							
Socio-economic scenario	WATW		ICARUS		Riders		Should I stay	
Climate scenario	C1	C2	C1	C2	C1	C2	C1	C2
No Adaptation	**1147**	**416**	**1147**	**416**	**1002**	**162**	**1817**	**1003**
EbA	504	137	504	137	171	137	1605	1003
MbA	580	580	580	580	399	0	1817	925
TbA	1147	1147	1147	1147	891	163	1889	925
PbA	1059	1059	1059	1059	865	147	1783	789

	Flood							
Socio-economic scenario	WATW		ICARUS		Riders		Should I stay	
Climate scenario	C1	C2	C1	C2	C1	C2	C1	C2
No Adaptation	**1293**	**1274**	**1573**	**1569**	**1349**	**1338**	**1922**	**1921**
EbA	1291	1274	1573	1569	1347	1338	1912	1908
MbA	1293	1274	1573	1569	1349	1338	1922	1921
TbA	1267	1255	1545	1537	1326	1326	1891	1874
PbA	1248	1236	1201	1376	1306	1300	1789	1782

	Food Provision							
Socio-economic scenario	WATW		ICARUS		Riders		Should I stay	
Climate scenario	C1	C2	C1	C2	C1	C2	C1	C2
No Adaptation	**1378**	**1815**	**1705**	**1809**	**964**	**1124**	**1413**	**1328**
EbA	1734	1849	1690	1788	923	1116	1406	1339
MbA	1574	1802	1881	1917	1020	1260	1416	1380
TbA	1910	1931	1864	1994	1072	1159	1628	1688
PbA	1814	1791	1717	1804	944	1094	1291	1260

Table 9: Results for Scotland (number of people vulnerable rounded to the nearest 10) for three vulnerability sectors, four socio-economic scenarios (Tartan Spring, Mad Max, Mactopia and The Scottish Play) and two climate scenarios (UKCP09 hot-dry and cool-wet).

	Biodiversity							
Socio-economic scenario	Tartan Spring		Mad Max		Scottish Play		Mactopia	
Climate scenario	Hot-dry	Cold-wet	Hot-dry	Cold-wet	Hot-dry	Cold-wet	Hot-dry	Cold-wet
No Adaptation	**8360**	**3040**	**6900**	**6100**	**7647**	**3327**	**3628**	**2140**
EbA	7420	3040	7560	6560	7535	3327	4178	1767
MbA	9310	1990	8550	6810	7035	3769	5063	3546
TbA	9880	5620	10370	7660	3098	2701	5768	1695
PbA	5070	1120	5900	5190	6805	1034	3938	839

	Flood							
Socio-economic scenario	Tartan Spring		Mad Max		Scottish Play		Mactopia	
Climate scenario	Hot-dry	Cold-wet	Hot-dry	Cold-wet	Hot-dry	Cold-wet	Hot-dry	Cold-wet
No Adaptation	**1900**	**720**	**320**	**320**	**718**	**390**	**236**	**236**
EbA	1900	720	320	320	718	390	236	236
MbA	1900	720	320	200	718	390	236	236
TbA	980	720	768	470	390	249	236	236
PbA	715	570	320	200	390	390	236	236

	Food Provision							
Socio-economic scenario	Tartan Spring		Mad Max		Scottish Play		Mactopia	
Climate scenario	Hot-dry	Cold-wet	Hot-dry	Cold-wet	Hot-dry	Cold-wet	Hot-dry	Cold-wet
No Adaptation	**35610**	**43880**	**28020**	**34040**	**34554**	**39347**	**42427**	**51020**
EbA	35860	43250	28440	34390	33485	39979	42828	50502
MbA	37020	40800	30700	35370	33690	40347	46523	52380
TbA	34680	44323	30140	36180	20978	38988	47630	50513
PbA	33780	38340	25950	33160	32147	35923	40611	46256

Robustness across scales: Comparing the results for Europe with those for Scotland, it can be seen that each of the policy archetypes has at least one sector for which the total number of vulnerable people is lower than with no adaptation. At this very broad level, therefore, each of the archetypes reduces vulnerability with respect to at least one sector, which suggests that there is robustness with respect to geographical scale.

Robustness across climate scenarios: In Table 8 for Europe, comparing the results of the different climate change scenarios (C1 and C2) shows that the MbA archetype is the only one that does not reduce vulnerability for both scenarios for at least one indicator, which suggests that MbA is less robust to the uncertainty regarding future climate. PbA reduces vulnerability for both climate scenarios for three of the four vulnerability indicators, but not for food provision in the We are the World and Icarus scenarios, where vulnerability is only reduced in the C2 scenario, which is cooler and wetter on average over Europe than the C1 scenario.
In Table 9 for Scotland, comparing the results of the hot-dry and cool-wet scenarios shows that the PbA reduces vulnerability for both climate scenarios for two of the three vulnerability indicators, but not for the flood indicator, where vulnerability remains the same in the hot-dry

scenario for Mad Max, the Scottish Play and Mactopia. Overall therefore, the PbA archetype reduces vulnerability across climate scenarios most frequently.

Robustness across socio-economic scenarios: Table 8 for Europe shows that for the biodiversity sector, for the C1 climate scenario, which has high emissions and high climate sensitivity, both PbA and EbA reduce vulnerability in all four socio-economic scenarios. Similarly, for water exploitation, both EbA and PbA reduce the number of vulnerable people in the C1 climate scenario. For the flood indicator PbA and TbA reduce vulnerability in all socio-economic scenarios. While for food provision none of the policy archetypes reduces vulnerability for all socio-economic scenarios using the C1 climate scenario.

Table 9 for Scotland shows that for biodiversity only the PbA archetype reduces vulnerability in all socio-economic scenarios, but only for the cool-wet scenario. For the flood indicator, PbA reduces vulnerability in Tartan Spring and Mad Max combined with the cool-wet climate scenario, but does not reduce vulnerability in the other two socio-economic scenarios. For food provision, again only the PbA archetype reduces vulnerability in all socio-economic scenarios. Overall therefore, the PbA archetype reduces vulnerability across socio-economic scenarios most frequently. As can be seen in Table 4, the PbA archetype includes increasing both human and social capital, which increases the coping capacity and, thus, reduces vulnerability even in scenarios such as Mad Max, in which society is very divided and resources are scarce.

Robustness across sectors: For Europe (Table 8), for the C1 climate scenarios, PbA reduces vulnerability in all sectors for all scenarios except for food provision in the We are the World and Mad Max scenarios. EbA reduces vulnerability in all sectors for all scenarios except for flood in Icarus and food provision in We are the World. Food provision vulnerability is not reduced at all by TbA and none of the other policy archetypes reduces food provision vulnerability in all socio-economic and climate scenarios. This is a result of the fact that the model on which the food provision results are based aims to satisfy the requirement of food provision. Thus, land is allocated for food provision as a first priority and adaptation options thus have only mixed success in reducing vulnerability.

For Scotland (Table 9), EbA reduces vulnerability for only 2 sectors. In particular EbA does not reduce vulnerability to flooding in any combination of socio-economic and climate scenarios. TbA, MbA and PbA reduce vulnerability in all three sectors. Overall, the PbA archetype reduces vulnerability in all sectors for all socio-economic scenarios except for the flood sector, where vulnerability is only reduced in the Tartan Spring scenario.

3.2 Results of testing "soft options"

The sorting of the options that cannot be tested using the IA Platform showed that these options were either PbA (e.g. education, early warning systems, institutional change) or MbA (e.g. taxes, subsidies, insurance). The PbA options that use and build human capital are robust across sectors. They are also robust across spatial scale. However, they are not robust across socio-economic scenarios, since some scenarios have strongly declining human capital in 2050 (e.g. Icarus, Mad Max, Tartan Spring). The PbA that use and build social capital through developing institutions and regulations are not necessarily robust across sectors, since regulations for one sector (e.g. coastal or urban) can affect another sector (e.g. agriculture, forestry). They are robust across scale, since the regulations and policy initiatives are in principle applicable at the EU and regional level. They are not robust across socio-economic scenarios, since in some scenarios there is very weak governance (e.g. Tartan Spring; Should I Stay or Should I Go), while in others governance is strong (Mactopia, We are the World). The MbA options are not robust across sectors because of cross-sectoral impacts. For example, changes to agricultural subsidies can affect water, forests, biodiversity, etc. The options are robust across scale, since they can achieve their expected outcomes at both the EU and regional levels. They are perhaps not robust across socio-economic scenarios, since 6 of the 8 scenarios have declining financial capital towards 2050 and only Riders on the Storm and Mactopia have increasing financial capital that could be mobilised for these options. Furthermore, the scenarios have very different levels of governance that would affect the implementation of many taxation options.

4. Uncertainty

Uncertainty was evaluated using a qualitative method to explore the propagation of errors through the linked meta-models of the IA Platform. This approach was supplemented by a quantitative method based on creating probability density functions (PDFs) of each of the Platform's input variables and sampling across these PDFs using Monte Carlo methods in order to undertake multiple runs of the IA Platform. Outputs from this approach can then be reflected as PDFs giving the uncertainty ranges associated with each output indicator (in this case for the vulnerability indicators described above). The qualitative and quantitative methods are described in detail in Annex 2 and Annex 3, respectively.

These approaches were used to rank the relative uncertainties associated with each of the vulnerability indicators. Annex 2 (Figure 5) provides categories of uncertainty for the principle IA Platform variables. This is an 8 class ranking from level 1 (lowest uncertainty) to level 8 (highest uncertainty). Assuming that the highest level of uncertainty applies to each vulnerability indicator then these can be ranked for Europe as: area flooded (level 4), people flooded (level 7), water exploitation index (level 8), food production (level 8), and biodiversity index (level 8).

Although a qualitative uncertainty analysis was not undertaken for Scotland, the IA Platform meta-models are the same as for Europe, and hence it is reasonable to assume the same ranking of uncertainties since these are primarily a function of the model structure. The high levels of uncertainty associated with the vulnerability indicators is not surprising since these are composite indices that accumulate uncertainties throughout the Platform's meta-model chain. It is evident, however, that vulnerability to flooding has a lower uncertainty than all of the other indicators. Interestingly, the policy archetypes were consistently effective in reducing vulnerability to flooding across archetypes and across scenarios. This suggests that some of the apparent ineffectiveness of policy adaptation for the other vulnerability indicators could, at least in part, be attributed to the uncertainties in calculating these indicators within the IA Platform.

Annex 2 (Figure 3) also indicates that the flooding indicator has the lowest variability across a range of scenarios suggesting again that the uncertainties due to alternative futures are less for this vulnerability indicator than for the others. The further analysis presented in Annex 3 shows that that there is no clear uncertainty bias between the scenarios, i.e. uncertainty is more a function of the vulnerability indicator than the scenario.

5. Discussion

The results show that the use of policy archetypes enables an analysis of policy robustness across scales, sectors and scenarios using the CLIMSAVE IA Platform and expert judgement. There are, however, some areas for improvement of the methodology. First, as noted in Section 3.1, the underlying philosophy of the model used for computing the vulnerability of food provision is that of achieving security. The vulnerability of food provision is therefore not a good indicator for the policy robustness testing. Second, the EbA policy archetype generally does quite well in reducing vulnerability in the various socio-economic scenarios across sectors and climate scenarios. However, as shown in Annex 1, one of the adaptation measures included in the EbA, increasing protected areas, was not working correctly in the version of the IA Platform used for the results reported here. This has since been corrected for the final version of the Platform. Third, the PbA policy archetype is generally the most robust option according to the results reported here. As noted in Section 3, this is clearly a result of the inclusion of two measures in this archetype that increase coping capacity. Finally, it should be noted that we have not explored the robustness of combinations of policy archetypes, which would indeed be more reflective of the reality of responding to vulnerability to climate and socio-economic changes. The methodology developed in this study would be suited to such an exploration of robustness of combinations of archetypes. The analysis also showed that the vulnerability to flooding had the lowest level of uncertainty associated with its calculation by the IA Platform. This is consistent with the observation that adaption options were generally positive for this indicator across policy archetypes and across scenarios.

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ANNEX 1: Input values for the IA Platform adaptation sliders

Scotland (all for 2050s):

	Slider values			Policy archetypes			
	Min	**Default**	**Max**	**EbA**	**MbA**	**TbA**	**PbA**
SOCIAL ADAPTATION OPTIONS:							
Water savings due to behavioural change (% change from current):							
Tartan spring	21,0	29,1	40,0				40,0
Mad Max	-56,7	-44,3	-31,9				-31,9
Scottish play	5,5	7,7	10,6				10,6
MacTopia	32,6	45,2	62,1				62,1
Change in dietary preferences for beef and lamb (% from current)							
Tartan spring	-21,0	-6,0	3,0				3,0
Mad Max	-6,0	10,0	26,0				26,0
Scottish play	-21,0	-9,0	0,0				0,0
MacTopia	-37,0	-21,0	-5,0				-5,0
Change in dietary preference for chicken and pork (% from current):							
Tartan spring	-21,0	-7,0	26,0				26,0
Mad Max	-6,0	10,0	26,0				26,0
Scottish play	-21,0	-9,0	12,0				12,0
MacTopia	-37,0	-21,0	-5,0				-5,0
ECONOMIC ADAPTATION OPTIONS:							
Change in food imports (% change from current):							
Tartan spring	-7,5	0,0	7,5		7,5		
Mad Max	-7,5	0,0	7,5		7,5		
Scottish play	-7,5	0,0	7,5		7,5		
MacTopia	25,5	30,0	37,5		37,5		

	Slider values			Policy archetypes			
	Min	**Default**	**Max**	**EbA**	**MbA**	**TbA**	**PbA**
Change in bioenergy production (% change from current):							
Tartan spring	0,3	1,7	2,3	2,3			
Mad Max	0,3	1,7	2,3	2,3			
Scottish play	0,3	1,7	2,3	2,3			
MacTopia	0,3	1,7	2,3	2,3			
TECHNOLOGICAL ADAPTATION OPTIONS:							
Change in agricultural mechanisation (%from current):							
Tartan spring	5,0	26,0	58,0			58,0	
Mad Max	3,0	15,0	36,0			36,0	
Scottish play	2,0	8,0	18,0			18,0	
MacTopia	5,0	26,0	58,0			58,0	
Water savings due to technological change (% from current):							
Tartan spring	21,0	29,1	40,0			40,0	
Mad Max	-60,9	-44,3	-31,9			-31,9	
Scottish play	5,5	7,7	10,6			10,6	
MacTopia	32,6	45,2	62,1			62,1	
Change in agricultural yields (% from current)							
Tartan spring	0,0	26,0	58,0			58,0	
Mad Max	26,0	58,0	98,0			98,0	
Scottish play	0,0	26,0	58,0			58,0	
MacTopia	26,0	58,0	98,0			98,0	
Change in irrigation efficiency (% from current):							
Tartan spring	12,0	26,0	58,0			58,0	
Mad Max	26,0	58,0	78,0			78,0	
Scottish play	-21,0	0,0	26,0			26,0	
MacTopia	12,0	26,0	58,0			58,0	

	Slider values			Policy archetypes			
	Min	**Default**	**Max**	**EbA**	**MbA**	**TbA**	**PbA**
ENVIRONMENTAL ADAPTATION OPTIONS:							
Reducing diffuse source pollution from agriculture (reduction of fertiliser and pesticides to reduce nitrate leaching) (% change from current):							
Tartan spring	0,9	1,0	1,1	1,1		1,1	
Mad Max	1,2	1,3	1,4	1,4		1,4	
Scottish play	1,0	1,1	1,2	1,2		1,2	
MacTopia	1,1	1,2	1,3	1,3		1,3	
Tree species for 5 regions (alpine, Atlantic, boreal, continental, Mediterranean) (drop-down menu of not changed, optimum or 5 species – Pinus sylvestris, Pinus halepensis, Pinus pinaster, Quercus ilex, Fagus sylvatica):							
Tartan spring		Not changed					
Mad Max		Not changed					
Scottish play		Not changed					
MacTopia		Not changed					
Forest management for the same 5 tree species as listed above (drop-down menu of Optimum, Un-evenaged, Even-aged):							
Tartan spring		Optimum			Even-aged	Optimum	Uneven-aged
Mad Max		Optimum			Even-aged	Optimum	Uneven-aged
Scottish play		Optimum			Even-aged	Optimum	Uneven-aged
MacTopia		Optimum			Even-aged	Optimum	Uneven-aged
Protected Area changed (% from current):							
Tartan spring	-40,1	-20,0	-12,5	-12,5			
Mad Max	-60,0	-40,0	-35,0	-35,0			
Scottish play	-50,1	-30,0	-19,0	-19,0			
MacTopia	-10,1	15,0	26,3	26,3			
Amount of Protected Area allocated to forest (% from current):							
Tartan spring		0,0		33,0			
Mad Max		0,0		33,0			
Scottish play		0,0		33,0			
MacTopia		0,0		33,0			

	Slider values			Policy archetypes			
	Min	Default	Max	EbA	MbA	TbA	PbA
Amount of Protected Area allocated to agriculture (% from current):							
Tartan spring		0,0		33,0			
Mad Max		0,0		33,0			
Scottish play		0,0		33,0			
MacTopia		0,0		33,0			
Method for allocating Protected Area (4 buttons – connectivity, connectivity then buffering, buffering then connectivity, buffering):							
Tartan spring		Connectivity		C then B			
Mad Max		Connectivity		C then B			
Scottish play		Connectivity		C then B			
MacTopia		Connectivity		C then B			
POLICY/GOVERNANCE ADAPTATION OPTIONS:							
Compact vs sprawled development							
Tartan spring	Low	Low	Medium	Medium			
Mad Max	Low	Low	Medium	Medium			
Scottish play	Medium	Medium	High	High			
MacTopia	Medium	High	High	High			
Attractiveness of the coast							
Tartan spring	Low	Low	Medium	Medium			
Mad Max	Low	Medium	Medium	Medium			
Scottish play	Low	Medium	High	High			
MacTopia	Medium	High	High	High			
Water demand prioritisation (drop-down menu of baseline, prioritising food production, prioritising environmental needs, prioritising domestic/industrial needs):							
Tartan spring		PropToBase		Env	Dom/Ind		
Mad Max		PropToBase		Env	Dom/Ind		
Scottish play		PropToBase		Env	Dom/Ind		
MacTopia		PropToBase		Env	Dom/Ind		

	Slider values			Policy archetypes			
	Min	Default	Max	EbA	MbA	TbA	PbA
Flood risk management adaptation approach (drop-down menu of flood protection upgrade, retreat of flood defences, implement flood resilience measures, implement a mixed response):							
Tartan spring		Upgrade		Retreat	Mixed	Upgrade	Resilience
Mad Max		Upgrade		Retreat	Mixed	Upgrade	Resilience
Scottish play		Upgrade		Retreat	Mixed	Upgrade	Resilience
MacTopia		Upgrade		Retreat	Mixed	Upgrade	Resilience
Flood risk management adaptation amount (4 buttons – no upgrade, 50%, 100%, 500%, 1000%):							
Tartan spring		No upgrade		Double	Yes	500,0	Yes
Mad Max		No upgrade		Maintain	Yes	No upgrade	Yes
Scottish play		No upgrade		Maintain	Yes	100,0	Yes
MacTopia		No upgrade		Double	Yes	1000,0	Yes
CAPITAL-BASED ADAPTATION OPTIONS:							
Human capital (5 buttons – H-, M-, no change, M+, H+):							
Tartan spring		M-					NC
Mad Max		M-					NC
Scottish play		H+					H+
MacTopia		H+					H+
Social capital (5 buttons – H-, M-, no change, M+, H+):							
Tartan spring		M-					NC
Mad Max		M+					H+
Scottish play		M+					H+
MacTopia		NC					M+
Manufactured capital (5 buttons – H-, M-, no change, M+, H+):							
Tartan spring		M+				H+	
Mad Max		M-				NC	
Scottish play		NC				M+	
MacTopia		M+				H+	

Europe (all for 2050s):

	Slider values			Policy archetypes			
	Min	**Default**	**Max**	**EbA**	**MbA**	**TbA**	**PbA**
SOCIAL ADAPTATION OPTIONS:							
Water savings due to behavioural change (% change from current):							
We are the world	32,6	45,2	62,1				62,1
Icarus	-41,3	-30,0	-21,6				-21,6
Should I stay or should I go	8,2	11,0	15,6				15,6
Riders on the storm	37,4	52,0	71,3				71,3
Change in dietary preferences for red meat (% change in ruminants from current):							
We are the world	-37,0	-21,0	-5,0				-37,0
Icarus	-6,0	10,0	26,0				-6,0
Should I stay or should I go	-11,0	0,0	26,0				-11,0
Riders on the storm	-21,0	-9,0	0,0				-21,0
Change in dietary preference for white meat (% change from current):							
We are the world	-37,0	-21,0	-5,0				-37,0
Icarus	-6,0	10,0	26,0				-6,0
Should I stay or should I go	-11,0	0,0	26,0				-11,0
Riders on the storm	-21,0	-9,0	12,0				-21,0
ECONOMIC ADAPTATION OPTIONS:							
Change in food imports (% change from current):							
We are the world	-19,0	-13,0	-9,4		-9,5		
Icarus	-10,5	-6,0	0,0		0,0		
Should I stay or should I go	-19,0	-13,0	-9,5		-9,5		
Riders on the storm	-19,0	-13,0	-9,5		-9,5		

	Slider values			Policy archetypes			
	Min	**Default**	**Max**	**EbA**	**MbA**	**TbA**	**PbA**
Change in bioenergy production (% change from current):							
We are the world	0,3	1,8	2,4	2,4			
Icarus	4,3	6,7	9,1	9,1			
Should I stay or should I go	0,3	1,8	2,4	2,4			
Riders on the storm	0,3	1,8	2,4	2,4			
TECHNOLOGICAL ADAPTATION OPTIONS:							
Change in agricultural mechanisation (%from current):							
We are the world	26,0	44,0	77,0			77,0	
Icarus	3,0	10,0	26,0			26,0	
Should I stay or should I go	2,0	5,0	15,0			15,0	
Riders on the storm	44,0	77,0	98,0			98,0	
Water savings due to technological change (% from current):							
We are the world	21,0	29,0	40,0			40,0	
Icarus	48,5	-35,0	-25,4			-25,4	
Should I stay or should I go	-82,9	-60,0	-43,4			-43,4	
Riders on the storm	32,6	45,0	62,1			62,1	
Change in agricultural yields (% from current)							
We are the world	-5,0	15,0	35,0			35,0	
Icarus	-21,0	-9,0	10,0			10,0	
Should I stay or should I go	-14,0	-3,0	36,0			36,0	
Riders on the storm	0,0	26,0	58,0			58,0	
Change in irrigation efficiency (% from current):							
We are the world	11,9	26,0	58,0			58,0	
Icarus	-25,0	-9,0	0,0			0,0	
Should I stay or should I go	-37,1	-21,0	0,0			0,0	
Riders on the storm	26,3	58,0	78,0			78,0	

	Slider values			Policy archetypes			
	Min	**Default**	**Max**	**EbA**	**MbA**	**TbA**	**PbA**
ENVIRONMENTAL ADAPTATION OPTIONS:							
Reducing diffuse source pollution from agriculture (reduction of fertiliser and pesticides to reduce nitrate leaching) (% change from current):							
We are the world	0,9	1,0	1,1	1,1		1,1	
Icarus	0,9	1,0	1,1	1,1		1,1	
Should I stay or should I go	1,0	1,1	1,2	1,2		1,2	
Riders on the storm	1,1	1,2	1,3	1,3		1,3	
Tree species for 5 regions (alpine, Atlantic, boreal, continental, Mediterranean) (drop-down menu of not changed, optimum or 5 species – Pinus sylvestris, Pinus halepensis, Pinus pinaster, Quercus ilex, Fagus sylvatica):							
We are the world		Not changed					
Icarus		Not changed					
Should I stay or should I go		Not changed					
Riders on the storm		Not changed					
Forest management for the same 5 tree species as listed above (drop-down menu of Optimum, Un-evenaged, Even-aged):							
We are the world		Optimum			Even-aged	Optimum	Uneven-aged
Icarus		Optimum			Even-aged	Optimum	Uneven-aged
Should I stay or should I go		Optimum			Even-aged	Optimum	Uneven-aged
Riders on the storm		Optimum			Even-aged	Optimum	Uneven-aged
Protected Area changed (% from current):							
We are the world	-19,9	10,0	24,4	24,4			
Icarus	-60,0	-40,0	-38,9	-38,9			
Should I stay or should I go	-50,1	-35,0	-33,2	-33,2			
Riders on the storm	10,2	25,0	47,6	47,6			
Amount of Protected Area allocated to forest (% from current):							
We are the world		0,0		33,0			
Icarus		0,0		33,0			
Should I stay or should I go		0,0		33,0			
Riders on the storm		0,0		33,0			

	Slider values			Policy archetypes			
	Min	**Default**	**Max**	**EbA**	**MbA**	**TbA**	**PbA**
Amount of Protected Area allocated to agriculture (% from current):							
We are the world		0,0		33,0			
Icarus		0,0		33,0			
Should I stay or should I go		0,0		33,0			
Riders on the storm		0,0		33,0			
Method for allocating Protected Area (4 buttons – connectivity, connectivity then buffering, buffering then connectivity, buffering):							
We are the world		Connectivity		C then B			
Icarus		Connectivity		C then B			
Should I stay or should I go		Connectivity		C then B			
Riders on the storm		Connectivity		C then B			
POLICY/GOVERNANCE ADAPTATION OPTIONS:							
Compact vs sprawled development							
We are the world	Medium	High	High	High			
Icarus	Low	Low	Medium	Medium			
Should I stay or should I go	Low	Low	Medium	Medium			
Riders on the storm	Medium	Medium	High	High			
Attractiveness of the coast							
We are the world	Medium	Medium (0,1)	High	High (0,5)			
Icarus	Low	Medium	Medium	High			
Should I stay or should I go	Low	Low	Medium	Medium			
Riders on the storm	Low	Low	Medium	Medium			
Water demand prioritisation (drop-down menu of baseline, prioritising food production, prioritising environmental needs, prioritising domestic/industrial needs):							
We are the world		PropToBase		Env	Dom/Ind		
Icarus		PropToBase		Env	Dom/Ind		
Should I stay or should I go		PropToBase		Env	Dom/Ind		
Riders on the storm		PropToBase		Env	Dom/Ind		

	Slider values			Policy archetypes			
	Min	**Default**	**Max**	**EbA**	**MbA**	**TbA**	**PbA**
Flood risk management adaptation approach (drop-down menu of flood protection upgrade, retreat of flood defences, implement flood resilience measures, implement a mixed response):							
We are the world		Upgrade		Retreat	Mixed	Upgrade	Resilience
Icarus		Upgrade		Retreat	Mixed	Upgrade	Resilience
Should I stay or should I go		Upgrade		Retreat	Mixed	Upgrade	Resilience
Riders on the storm		Upgrade		Retreat	Mixed	Upgrade	Resilience
Flood risk management adaptation amount (4 buttons – no upgrade, 50%, 100%, 500%, 1000%):							
We are the world		No upgrade		Maintain	Yes	500,0	Yes
Icarus		No upgrade		No creation	Yes	No upgrade	Yes
Should I stay or should I go		No upgrade		No creation	Yes	No upgrade	Yes
Riders on the storm		No upgrade		Double	Yes	500,0	Yes
CAPITAL-BASED ADAPTATION OPTIONS:							
Human capital (5 buttons – H-, M-, no change, M+, H+):							
We are the world		H+					H+
Icarus		H-					M-
Should I stay or should I go		M-					NC
Riders on the storm		H+					H+
Social capital (5 buttons – H-, M-, no change, M+, H+):							
We are the world		M+					H+
Icarus		NC					M+
Should I stay or should I go		M+					H+
Riders on the storm		M+					H+
Manufactured capital (5 buttons – H-, M-, no change, M+, H+):							
We are the world		M+				H+	
Icarus		M-				NC	
Should I stay or should I go		M-				NC	
Riders on the storm		M+				H+	

ANNEX 2: Qualitative uncertainty analysis (based on a paper submitted to Climatic Change)

The importance of considering cross-sectoral uncertainty in climate change and adaptation assessments

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Abstract

In this paper we present an uncertainty analysis of a cross-sectoral, regional-scale, Integrated Assessment Platform (IAP) for climate change impact, adaptation and vulnerability assessment. The IAP couples simplified meta-models for a number of sectors (agriculture, forestry, urban development biodiversity, flood and water resources management) within a user-friendly interface. Cross-sectoral interactions and feedbacks can be evaluated for a range of future scenarios with the aim of supporting a stakeholder dialogue and mutual learning. We present a method to address uncertainty in: (i) future climate and socio-economic scenarios and (ii) the interlinked meta-model network. A mixed-method approach is taken: formal numerical approaches, modeller interviews and network analysis are combined to provide a holistic uncertainty assessment that considers both quantifiable and un-quantifiable uncertainty. Results demonstrate that the combined quantitative-qualitative approach provides considerable advantages over traditional validation-based uncertainty assessments. Combined fuzzy-set methods and network analysis methods allow maps of modeller certainty to be explored. The results indicate that validation statistics are not the only factors driving modeller certainty; a large range of other factors including validation data quality and availability, the meta-modelling process, inter-modeller trust, derivation methods, and pragmatic factors such as time, resources, skills and experience influence modeller certainty. We conclude that by identifying, classifying and exploring uncertainty in conjunction with the model developers, we can ensure not only that the modelling system itself improves, but that the decisions based on it can draw on the best available information: the projection itself, and a holistic understanding of the uncertainty associated with it.

1. Introduction

The future is uncertain. Although the reality of climate change is now rarely questioned, the impacts that mankind will experience are ultimately unknowable. These impacts depend not only on complex interactions between physical environmental parameters, but also on social, political and economic decisions. The “unknowable” cannot be a barrier to decision-makers: decisions need to be made in order to plan for the future. Environmental models are important tools in helping to inform decisions since they allow explorations of the future that cannot be achieved through observation. Many models have been developed to explore the impacts of climate change and potential adaptation opportunities (Turnpenny et al., 2004). These models have tended to be embedded within single socio-economic sectors or individual components of the environment (Mohrech et al., 2008; Trnka, 2010). However, these interact in often complex and conflicting ways. For the best-informed environmental decision-making no single sector can be considered in isolation from the others. To address this issue, integrated assessment approaches have been developed that facilitate the integration of knowledge-bases (Audsley et al., 2008; Holman et al., 2008).

Integrated assessment provides significant opportunities for exploratory analysis of our unknowable future. However, each knowledge source brings with it a different projection of the future with a different level of certainty. An assessment of these uncertainties and how they interact across an integrated assessment is essential in supporting robust decision-making. Without an understanding of uncertainty decision-makers will find it impossible to navigate the tricky path between relativism (where every future is equally possible, so it doesn't make a difference which choices we make) and model-based determinism (where the future predicted by the integrated assessment is seen as definitive).

Traditional approaches to uncertainty analysis draw heavily on the physical sciences (Beven, 2012; Latour and Woolgar, 1979; Wynne, 1992) with a strong reliance on quantitative approaches. Whilst these approaches address the question "to what extent does the data fit with the baseline validation data?", the real question when addressing uncertainty for decision-making is: "to what extent is the model output likely to project the real-world future values of the variable it is intended to replicate?". Addressing this question requires a holistic understanding of the differences not only between the model and the validation data, but the full chain of human and mathematical factors that affect the extent to which the output of the assessment differs from what the *real world* parameter of interest would be in a given scenario.

In an integrated assessment approach uncertainty derives from two major sources: (i) *scenario uncertainty*: uncertainties associated with the development of alternative climate and socio-economic futures; and (ii) *model uncertainty*: the model's capacity to replicate future conditions and processes, the magnitude of error propagation through integrated modelling systems and the uncertainties in their underlying datasets. The aim of the paper is to present the approach to assessing scenario and model uncertainty developed within the Integrated Assessment Platform (IAP) of the CLIMSAVE project (Harrison et al., 2013). The IAP combines 10 sectoral meta-models (Table 1) and is designed to run quickly over a web interface.

2. Scenario Uncertainty

Scenario uncertainty is fundamentally unknowable and as such highly difficult to quantify. The CLIMSAVE approach addresses scenario uncertainty by: (i) identifying internally consistent futures based on the best available knowledge and expert opinion; and (ii) allowing users to define their own future scenarios. The online nature of the IAP allows users to do this using a web-browser without the need for specialist software.

2.1. Uncertainty in climate futures

The CLIMSAVE IAP addresses climate scenario uncertainty by representing multiple projections of future climate related to different sources of uncertainty (greenhouse gas emissions, global climate models (GCMs) and the sensitivity of the climate system). However, in order to keep the number of combinations to manageable levels, four SRES emissions scenarios (A1b, A2, B1 and B2), three climate sensitivities (low, medium and high) and five GCMs are included in the IAP. The IPCC-AR4 database (IPCC DDC, 2010) was used as a sampling frame from which to select five GCMS from the sixteen available. First GCMs which did not include all the climate variables required by the meta-models were omitted. Then GCM outputs were compared on a grid cell basis with current climate observations and the central value of all sixteen GCMs to determine a representative set of five GCMs. This consisted of the model that best replicated current observations (MPEH5), the model that best represented the central tendency of the 16 GCMs (CSMK3), and three GCMs which were selected to preserve as much of the variability in the projections of climate space from the 16 models (based on the Euclidean distance in an 8-dimensional space consisting of seasonal changes of precipitation and temperature). These models were GFCM21, HADGEM and IPCM4.

Figure 1 demonstrates some of the climate scenario uncertainty that the stakeholders can explore by showing a moderate and an extreme climate projection. The "moderate" projection used the least extreme GCM (IPCM4), low climate sensitivity and the B2 emissions scenario; the "extreme" projection used the most extreme GCM (GFCM21), high climate sensitivity and an A1b emissions scenario. The difference between the two climate projections is significant with the extreme scenario presenting a considerably warmer, drier Europe for the majority of southern and central Europe. The five selected GCMs address the uncertainty in future climate by considering not only the quality of the available models, but by representing their diversity in terms of potential climate outputs. This flexibility in scenario definition underlines that no one climate future is more likely than another, reflecting the uncertainty inherent in the unknowable future climate.

Table 1: The 10 models included in the CLIMSAVE IAP (adapted from Harrison et al., 2013).

Meta-model	**Sector**	**Original model**	**Meta-modelling approach**
RUG	Urban growth	Regional Urban Growth (RUG) (Reginster and Rounsevell 2006)	Look-up tables
Yields	Crop yields	ROIMPEL (Audsley et al. 2008)	Soil/climate clustering combined with artificial neural networks
Pests	Crop pests	CLIMEX (Sutherst et al. 2001)	Artificial neural networks
Meta-GOTILWA	Forest Management	GOTILWA+ (Morales et al. 2005)	Artificial neural networks
SFARMOD	Land profitability/ land use	SFARMOD (Holman et al. 2005)	Soil/climate clustering combined with artificial neural networks
WATERGAP	Water availability/consumption	Water - Global Assessment and Prognosis (WaterGAP3) (Verzano 2009)	3-dimensional surface response diagrams
FLOODMODEL	Flood impacts	RegIS2 (Mokrech et al. 2008) and DIVA (McFadden et al. 2007)	Simplified process-based model
SPECIES	Bioclimatic suitability for biodiversity	SPECIES (Harrison et al. 2006)	Artificial neural networks
LPJ-GUESS	Forest growth and development	LPJ-GUESS (Sitch et al. 2003)	Look-up tables
Snow	Snow days / volume; Ski days	SnowMAUS snow cover simulator (Trnka et al. 2010)	Artificial neural networks

Figure 1: Differences between climate change scenarios for the 2050s presented within the CLIMSAVE IAP: extreme and moderate examples.

	An extreme scenario: GFCM21; A1; High sensitivity	A moderate scenario: IPCM4; B2; Low sensitivity
0.0 to 0.5 (°C) 0.5 to 1.0 (°C) 1.0 to 1.5 (°C) 1.5 to 2.0 (°C) 2.0 to 2.5 (°C) 2.5 to 3.0 (°C) 3.0 to 3.5 (°C) 3.5 to 4.1 (°C)		
Mean Temperature	Maximum increase: +4.1°C	Maximum increase: +2.2°C
-64.2 to -50.0 (%) -49.9 to -40.0 (%) -39.9 to -30.0 (%) -29.9 to -20.0 (%) -19.9 to -10.0 (%) -9.9 to 0.0 (%) 0.1 to 10.0 (%) 10.1 to 20.0 (%) 20.1 to 24.1 (%)		
Precipitation	Change : -64.2 to +24.1%	Change: -21.1 to +7.6%

2.2. Uncertainty in socio-economic futures

The CLIMSAVE IAP addresses uncertainty in socio-economic scenarios by following a participatory approach. Such approaches bring together diverse knowledge from different sectors of society (governments, civil society, business and research), fields of study (including different environmental sectors) and geographic regions to define relevant social, political, economic and technological variables that are needed for impact model assessments (Rounsevell and Metzger, 2010). Stakeholders were invited to 3 two-day workshops held over an 18-month period to discuss what they saw as the main uncertainties facing the EU. They voted to identify the two main uncertainties in terms of their 'Importance' and 'Uncertainty'. The selected uncertainties, "whether economic development was gradual or rollercoaster" and "whether innovation was effective or not", were then used as the axes of a coordinate system delimiting four scenarios for which storylines were developed (Kok et al., 2011).

Integration of the qualitative storylines with the quantitative sectoral meta-models within the IAP required translation across the qualitative-quantitative divide. Similar studies have quantified model input in an *ad-hoc* way, which does not do justice to either the richness of the storylines or the quantitative complexity of the models (Alcamo et al., 2008). To avoid this, a "Fuzzy set" approach (Kok, 2009) was used. Parameters were assessed directly by the stakeholders and qualitative statements were used to describe changes, e.g. "Europe will experience a *moderate increase* in population". The stakeholders were then asked to parameterise these using their expert judgement and quantify, for example, what is meant by a 'moderate increase' thus maintaining the qualitative storylines, whilst providing quantitative values. The method is relatively quick and straightforward to perform during a stakeholder workshop. Even so, there was only time for the stakeholders to directly enumerate seven priority variables; the remaining variables were quantified by the CLIMSAVE scenario experts working in collaboration with the modellers. The quantified values were used to set the default values for a range of socio-economic scenario sliders on the IAP. Figure 2 shows an example of these values for the 2050s for the utopian "We are the world" scenario (WRW; stable economy and successful innovation) and the dystopian "Should I stay or should I go" scenario (SOG; innovation fails and economic growth is a rollercoaster decline). The default values for the SOG scenario indicate a greater focus on compact settlements, with a higher population than the WRW scenario but inflated oil and timber prices, significantly less GDP, and (as innovation fails) lower water saving and irrigation efficiency due to technological change and less improvements in agricultural mechanisation.

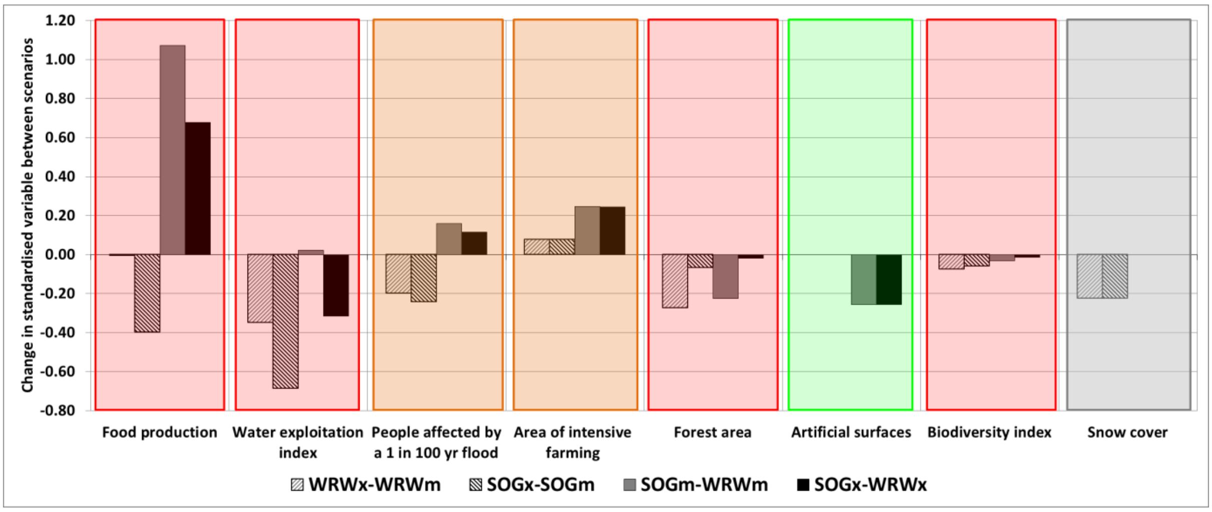
Figure 2: Representing socio-economic scenario uncertainties on the CLIMSAVE IAP. A traffic-light system is used to differentiate the 'scenario-plausible range' (shown in green) from slider values considered to be outside the scenario (shown in yellow).

To account for the inherent uncertainty in the socio-economic futures, the CLIMSAVE IAP allows exploration of a range of values around the default associated with each scenario. Guidance is provided, via a traffic-light colour coding system which indicates as a green range values that are considered to be "plausible" under the selected socio-economic storyline. Values in the yellow (amber) area of each slider can still be explored, but are considered to be outside of the bounds of the selected scenario, and should be interpreted as such. The red ranges are considered (by the IAP modellers) to be so extreme that they are unrealistic in the given scenario.

2.3. Exploring scenario uncertainty

Figure 3 explores climate and socio-economic scenarios in tandem by combining the moderate and extreme climate scenarios with the utopian and dystopian socio-economic scenarios introduced in Figure 1 and Figure 2 in terms of their impacts on eight key sectoral variables. It shows that, whilst the exact future may be uncertain, the extent to which socio-economic and climate drivers may affect different impact variables can be explored. In an urban context, for example, socio-economic factors are the greatest source of scenario uncertainty as the modelled area covered by artificial surfaces is not influenced by climate. Similarly, uncertainty with respect to snow cover is entirely driven by climatic factors, with no socio-economic influence. Most other variables have significant uncertainty from both climatic and socio-economic sources, but to different extents. In the SOG scenario, where innovation is failing and population is increasing, food production is the primary focus at the expense of other land use sectors and this is reflected across a number of the variables: food production and intensive agriculture are greater and forest area and biodiversity are lower.

Figure 3: Exploring climate, scenario and model uncertainties using the CLIMSAVE IAP. Values are European mean values from IAP output standardised by the European mean of all four scenarios. Values are calculated so that negative values indicate a lower value in an extreme scenario with respect to the linked moderate scenario. The water exploitation index has been inverted; lower values indicate greater stress.



Differences driven by climate												
Differences driven by socio-economics												
Model uncertainty (box colour)	Least										Greatest	

Similarly, in the warmer, drier climate extreme scenario, there is significantly greater water stress (lower water exploitation index; WEI), a decrease in river flooding[6], an increase in intensive farming and a reduction in forest area that might be expected as a result of the warmer drier conditions. The IAP also highlights the complex interactions between the climate and socio-economic scenarios: very few of the paired climate or socio-economic bars in Figure 3 are of equal length. This shows that, for example, whilst climate may contribute to a significant decrease in food production in the SOG scenario, in the WRW scenario the

[6] Coastal flooding is unchanged as the sea-level variable is constant across the climate scenarios.

climate has very little influence potentially due to the increased water efficiency leading to more water availability for irrigation. Similarly, whilst socio-economic factors in the WRW scenario may lead to increases in food production under both extreme and moderate climate scenarios, the increases possible are considerably greater in the moderate scenario.

3. Model uncertainty

Model uncertainty in the CLIMSAVE IAP derives from the fact that: (i) models are simplifications and reflect the assumptions within them and the quality of their input data; (ii) the IAP meta-models are further simplifications, emulators of more complex models designed to run in a timeframe appropriate for a web-based system; and (iii) *compound uncertainty* will result as outputs from one model are passed to another within the integrated system. Here, model uncertainty is explored by drawing on both traditional quantitative validation assessments and a new-mixed methods approach that assesses the "holistic uncertainty" as perceived by the meta-modellers themselves.

3.1. Exploring uncertainty in a meta-modelling network

Quantitative validation assessments were collected from each meta-modelling team in an "uncertainty data dictionary" (UDD). For each output variable meta-modellers were asked to include their approach to data validation and the validation results achieved. Fuzzy set methods (see section 2.2) were then used to capture both quantitatively and qualitatively the meta-modellers' confidence in their variables. The meta-modellers were asked, for each variable, to consider "holistic uncertainty": i.e. *their (un)certainty that the variable represents the real world aspect it is intended to* and the full chain of factors that influence this. These factors include: (i) the complexity of the impact modelled; (ii) the appropriateness of the modelling approach; (iii) the data used; and (iv) the approach to validation. Each meta-modeller was asked to rank their output variables in order of confidence. They were then asked to fit their variables into a five class system from "Very High" to "Very Low" confidence. Where necessary, modellers were allowed to add extra sub-classes with reference to one of the original five classes as a parent class. These qualitative statements were then quantified by the meta-modellers fitting a percentage probability to each class again with reference to *holistic* uncertainty rather than to validation statistics alone. Table 2 shows a comparison of the listed output provided by two of the modellers.

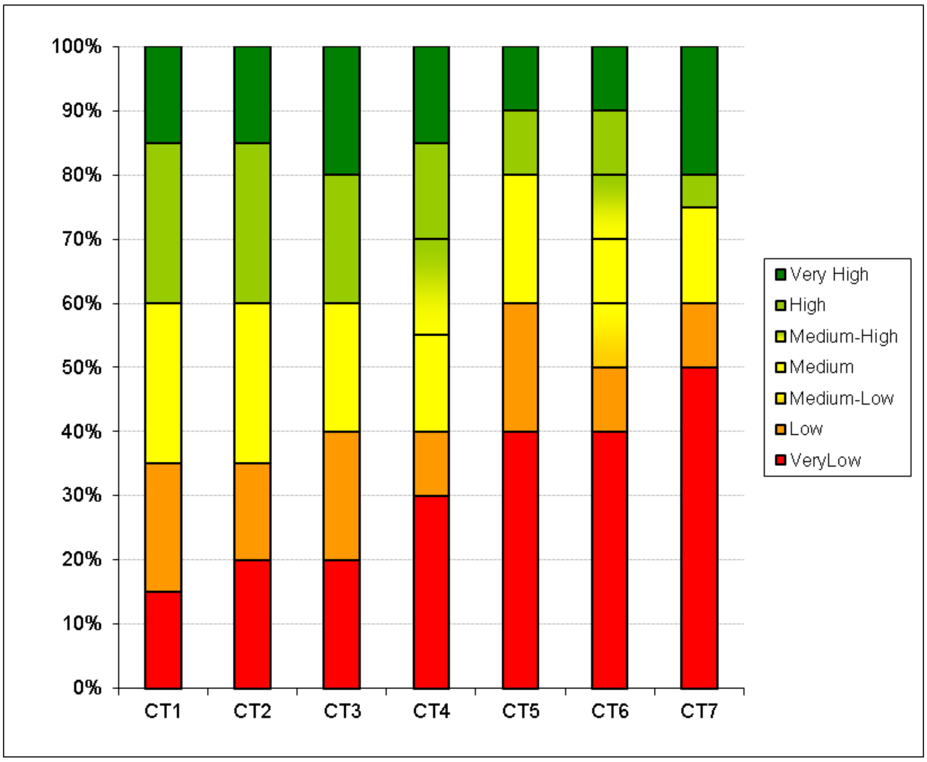
Seven different classification typologies (CT1-7) were identified (Figure 4). There are significant differences between the typologies: the very low class, for example, ranges in size from "<15%" (CT1) to "<50%" (CT7). Also, many of the classes overlap considerably: CT7 has "medium" ranging from 60-70%, entirely within the "high" range of CTs 1, 2 and 3. Some meta-modellers (CT4 and CT6) felt the need to break the medium class down into two or three subclasses. These differences are important as they give the individual modellers the ability to fit the classification to match the levels of uncertainty most commonly found in their data.

Table 2: Output variable classification for two of the CLIMSAVE modellers showing the ranking of variables within a certainty range and the quantification values of the fuzzy linguistic classifications.

Model	Classification	Variable(s)	Values
Yields, Snow & Pests	Very High	1) SnowDays; SkiDays; SnowVolume	90-100%
	High	2) EI; NG ; Sowing; Harvesting	80-90%
	(Medium High)		70-80%
	Medium	3) YieldPYAv	60-70%
	(Lower Medium)	4) PlYAv 5) YAv	50-60%
	Low		40-50%
	Very Low		<40%

Model	Classification	Variable(s)	Values
WATERGAP	Very High		80-100%
	High	1) WA	60-80%
	Medium	2) Qavgn 3) Wapercap	40-60%
	Low	4) Q95n; Q5n 5) QMED; ES-reg; Wairr 6) Wutot; satWWDom; sat WWele; 7) chngWTAEU; Q95; Q5; Qavg; WTA	20-40%
	Very Low		<20%

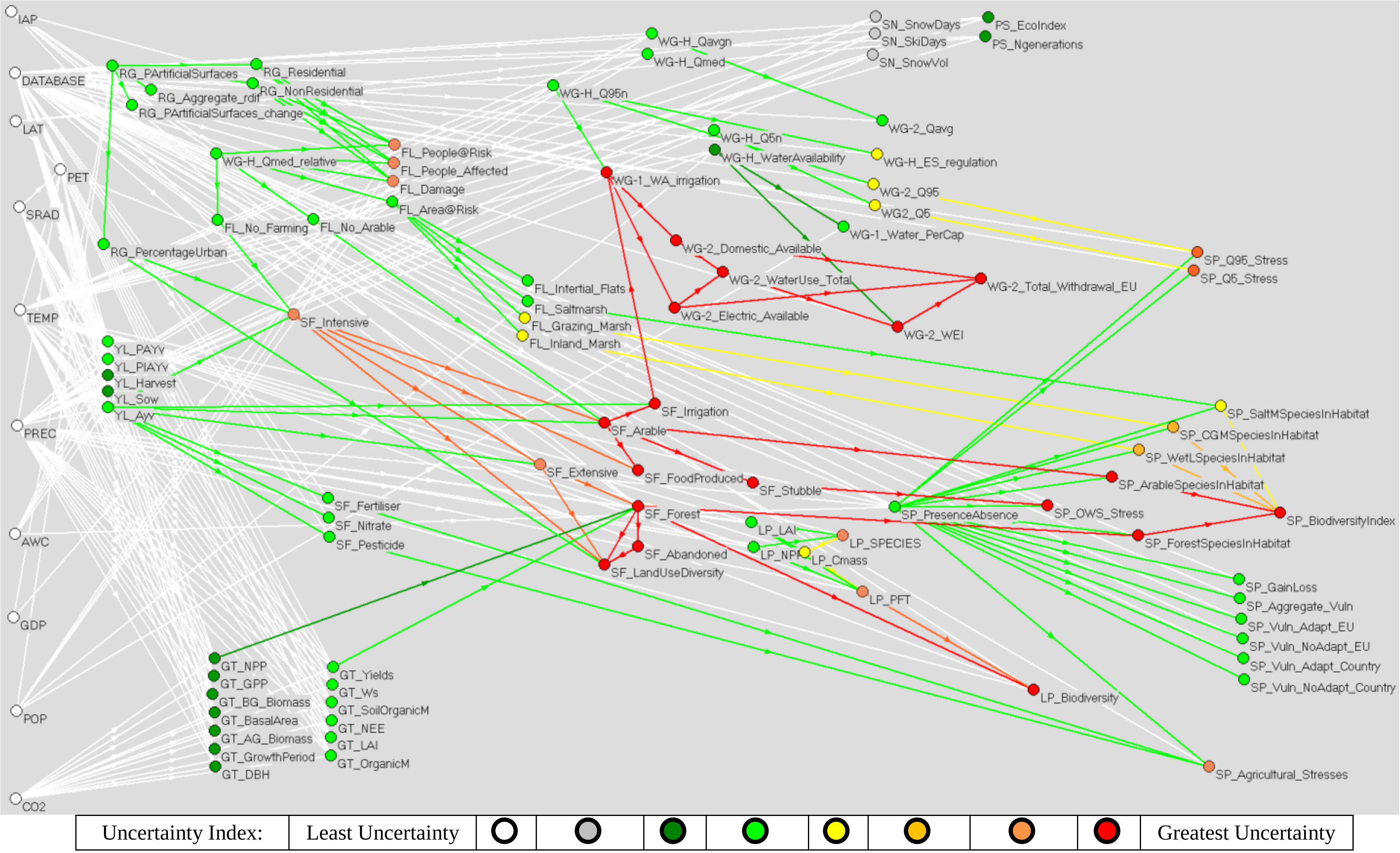
Figure 4: Certainty typologies identified by the meta-modellers.



Modellers identified the input and output variables from their model and a variable-to-variable (V2V) network of the IAP was created using a customised MS Excel spreadsheet, FCMapper (FCMapper, 2012) and Pajek network analysis software (Pajek, 2012). The resultant network comprised 324 nodes and 952 vertices. To simplify the network, any variables coming from the IAP or from the model-specific databases were condensed into single linkages. The justification for this was that IAP variables are defined input parameters and as such are without error. Model-specific database input variables will contain uncertainty, however, the expert classification of output variable certainty is intended to reflect all aspects that influence whether or not that variable reflects real world conditions – which includes the sum of all issues with the input variables. The final variable-to-variable network (Figure 5) contained 95 vertices (nodes, points) and 272 arcs (lines, edges: with direction). Initial certainty values for each node were set to the maximum of the class allocated by the fuzzy set method (Figure 4) with percentages converted to a value between 0 and 1. Compound uncertainty throughout the network was then calculated by multiplying the certainty values of each node by the certainty of all nodes higher up the model chain.

The V2V network provides a number of key insights into model uncertainty. Generally, uncertainty increases for nodes dependant on numerous inputs (e.g. the summary biodiversity index from SPECIES: SP_BiodiversityIndex). This reflects the methodology used but is reasonable and matches expectations with respect to compound uncertainty. Importantly, the number of inputs is not the sole driver; input quality is also important. For example, the SPECIES model's "presence of species within saltmarsh habitat" (SP_SaltMSpeciesInHabitat) has higher certainty than the equivalent variable for coastal grazing marsh (SP_CGMSpeciesInHabitat) despite both variables having equal number of inputs. This reflects the greater confidence in FLOODMODEL with respect to saltmarsh area (FL_Saltmarsh) over coastal grazing marsh (FL_Grazing_Marsh). Furthermore, the V2V map identifies variables which are independent of the majority of the uncertainty within the network (e.g. snow model (SN); Meta-GOTILWA (GT)). These models rely for the most part on standard climate data and data from their own databases and, as such, maintain the high levels of confidence initially ascribed to them. Also, the V2V network highlights critical nodes whose level of certainty has a strong influence on nodes further down the chain (e.g. WaterGAP's Water abstraction for irrigation: WG-1_WA_irrigation). These nodes should be prime targets for modeller's efforts to improve certainty, and if the maximum certainty possible is achieved, this should be recognised as a key factor affecting the certainty of the dependant nodes. The V2V network has significant utility as a discussion tool providing modellers with the data needed to contextualise further discussions of inter-model certainty. This is enhanced through displaying the validation data (e.g. R^2/kappa values etc.) at each node.

Figure 5: Variable-to-variable network of the CLIMSAVE IAP. Note that variables are classified in terms of their uncertainty. Node labels are variable names. The first two letters correspond to the originating model:RG = RUG; FL = FLOODMODEL; GT = Meta-GOTILWA; LP= LPJ-GUESS; PS= Pests; SF = SFARMOD; WG=WATERGAP; SP = SPECIES; SN= Snow; YL=Yields.



3.2. Modeller interviews

To understand the factors driving modeller uncertainty each of the individual meta-modellers was interviewed. These interviews drew on the information recorded in the UDDs and were performed using text-based Skype. This method put the modellers in direct control of the transcript of the interviews which ranged from between one to three hours in length. The interviews were semi-structured and performed in tandem with the fuzzy set data collection.

3.2.1. Validation

Validation was a key factor influencing modeller certainty. For some variables insufficient data were available to validate output, or available data were at an inappropriate scale or resolution. For example, validation data for "the standard of flood protection" is only possible where flood protection data have been collected. This tends to be in countries at risk at present, rather than potentially at risk in the future. Similarly, crop yield data are not collected at a European scale; the best available validation data are outputs from other models. In this example, confidence in the validation data is shown to be a key driving factor in certainty. Despite high validation statistics ("99% or better") compared with the other modelled output, the fact that this model has itself only been validated for subsets of Europe (Bulgaria/Czech Republic) affects modeller confidence to the point that they class their confidence as "40 to 60%". It is clearly not just the *availability* of validation data that modifies certainty with regard to a model's output, but the *perceived quality* of that validation data.

The *validation method* also influences modeller certainty. In the SPECIES model, where the kappa index of agreement (Monserud and Leemans, 1992) and AUC curve (Swets, 1988) were used as validation statistics, the modellers reported that when determining which future projections to include in the IAP the modelling team would discuss how the distributions matched their expectations. They noted that, for species with very wide spatial distributions, high kappa and AUC scores often reflect the fact that the species is projected to occur everywhere rather than supporting an argument that the neural network is accurately projecting the future species distribution. Conversely, they argued that for species with a patchy distribution (where the patchiness reflects factors other than climatology, such as land-use, species management, competition or predation) a projection might improve confidence in the predictive power of the neural network if the projection highlights bioclimatic regions where a species may plausibly occur in the absence of these factors even if the kappa is poor as a result of the patchiness. These examples demonstrate the dangers of over-emphasising the reported quantitative uncertainty assessments, and stress the importance of a holistic approach that considers the extent to which the model output reflects the real world aspect that they seek to represent.

3.2.2. Derived variables: levels of abstraction

The "level of abstraction" was the factor most commonly used by the modellers to explain why they chose to rank one variable lower than another. This included all areas where one variable was derived from another (e.g. through statistical modelling, interpolation or extrapolation). The separation of the ranking and classification steps in the fuzzy set approach was very useful for teasing out these differences. The abstraction process often had no influence on the overall class to which the derived variable was allocated, but was often different enough to place the variable one rank lower than its parent. The complex internal breakdown of the "Low" class of the WATERGAP meta-model (Table 2) provides a good example of this. In most cases, when discussing the ranking of variables modellers used qualitative terms in relation to parent variables without any explicit reference to the derived variable's validation statistics. This will likely reflect the ease of the fuzzy set approach and the time available within the interview to research variable validation data. Furthermore, validation data for derived variables may not always be available in situations where there is validation data for the parent variable (which may be the reason it is being modelled and not measured in the first place). Also, in some circumstances validation may be impossible, as it is for all future projections, or unnecessary due to the minimal level of approximation involved. Whilst the latter case may not be best scientific practice it is likely to occur in reality: is the measurement of the total length A+B independently validated when lengths A and B have already been validated separately?

3.2.3. Incomplete knowledge and other people's data

Modellers' knowledge of the validation of the data they base their validations on was often incomplete. For example, they might know how well their model output matches with a land cover validation dataset, but be unaware of the extent to which this dataset matches real world land-cover (presumably as reported in the land cover dataset's own validation documentation). Considering holistic uncertainty forces this to be addressed as well as the fact that land cover changes over time. Whilst factors such as this vary in terms of their significance, it is important to be aware of them to be able to contextualise the certainty of any modelling output. Also, many modellers expressed greater uncertainty when working with datasets they were less familiar with including inputs from other models. It is here that presenting the qualitative and quantitative data through the V2V network analysis can help modellers to better improve their understanding of the interactions between models. In addition, future comparative analysis of the V2V network based on modeller interpretation and cumulative uncertainty can help identify, quantify and negotiate the disparities.

3.2.4. Making a meta-model

For some modellers, the process of creating a meta-model to emulate a more complex model had the most significant impact on the certainty of their model (particularly for LPJ-GUESS, WATERGAP and Meta-GOTILWA). In most cases this was because the original model was considerably more powerful, used more detailed input data and often better represented the processes being modelled. The LPJ-GUESS model, for example, includes rules to describe competition and succession for plant species, whereas the LPJ-GUESS meta-model is a statistical function driven solely by temperature, precipitation and CO_2. The fuzzy set approach allows the impact on the certainty resulting from the meta-model creation process to be assessed. For LPJ-GUESS, the meta-model creation led to a decrease in the accuracy class for all variables, with one variable dropping from high (60-85% certainty) to low (10-35%) certainty (Table 3).

Table 3: Fuzzy set classification of: (i) the LPJ-GUESS original model and (ii) its meta-model.

(i)

Model	Classification	Variable(s)	Values	Midpoint
LPJ-GUESS (Model)	Very High		85-100%	0.92
	High	1) LAI/NPP 2) Cmass	60-85%	0.72
	Medium	3) Biodiv	35-60%	0.47
	Low		10-35%	0.22
	Very Low		<10%	0.05

(ii)

Model	Classification	Variable(s)	Values	Midpoint
LPJ-GUESS (Meta-model)	Very High		85-100%	0.92
	High		60-85%	0.72
	Medium	1) LAI/NPP	35-60%	0.47
	Low	2) Cmass 3) Biodiv	10-35%	0.22
	Very Low		<10%	0.05

3.2.5. Pragmatism: time, data, money and skills

A number of pragmatic factors were raised by modellers as key influences on their certainty. More time to allow more improvement and checking was often raised. Better data (both input and validation) was also stressed. This included issues related to data being unavailable at the appropriate scale or resolution or data unobtainable due to cost or licensing reasons or because there was insufficient time to convert the data to a useable format. Skills were also mentioned, staff changeovers have knock-on effects on the work possible, the data collected and the time work would take. Working with a web-based IAP needed skills in programming languages that were capable of processing at high speeds, often a different language to that the model was originally written in. This meant that modellers often had to rapidly develop new skills and/or convert existing models from one programming language to another. This again had knock-on impacts in terms of time available and the level of validation it was possible to achieve. Experience was also a factor: for some modellers this was the first time that a meta-model had been created from their model, and a lot was learned in the course of the IAP development. This independent learning situated within institutions and individuals can be a key factor affecting not only the individual's confidence with a model, but the level of certainty attainable within a time period. Subsequent projects, able to capitalise on existing knowledge, are more likely to be able to achieve greater certainty, as many "wrong-turns" will already have been explored, existing datasets can be built on and better datasets can be acquired.

3.3. Combining scenario and model uncertainty

The approaches developed and applied within the IAP have provided a considerable depth of data on both scenario and model uncertainty. However, these are not treated as separate entities within the IAP. Any interpretation of the impacts simulated by the IAP for the scenarios contained within it need to consider both the diversity of other equally plausible scenarios and the extent to which the modelled impacts reflect the world that would exist if that scenario took place. By extracting model uncertainty from the variable-to-variable network and overlaying it as a lens through which the scenario uncertainty is interpreted, scenario and model uncertainty can be explored in tandem (Figure 3). Doing so shows that the artificial surfaces and snow cover variables have considerably less of both types of uncertainty. Knowing this provides invaluable context to an interpreter of the IAP output. With respect to urban growth, they know that the modeller is relatively confident in the output for artificial surfaces and that it is solely driven by socio-economic change rather than climate change. Similarly, by consulting Figure 3 and the V2V network they can identify that certainty with respect to the WEI is driven by a particularly critical node (WG-1_WA_irrigation), and that the modellers have greater confidence in the water availability component (WG-H_WaterAvailability) of WEI than the water use component (WG2-WaterUSe_Total). By providing this context, the combined uncertainty assessment provides considerable additional information over that available from standard validation approaches and allows two forms of uncertainty, both of which are difficult to quantify precisely, to be considered at the same time.

4. Discussion

The CLIMSAVE IAP is an exploratory tool, which aims to address uncertainty by presenting decision-makers with a range of possibilities rather than directing them towards a definitive vision of the future. Using the IAP to explore a broad range of scenarios will help to determine if a particular impact is common to many scenarios, or likely only when particular scenario parameters are selected. This, in turn, can help support robust decision-making as the decisions needed will vary with both the severity and the likelihood of the impacts identified. As a further extension, an automated version of the IAP will be used to take a probabilistic approach (see Annex 3). By running the IAP multiple times using a targeted sample across the key climatic and socio-economic input variables it will be possible to identify whether futures for each sector tend to converge (similar patterns of impact result from multiple scenarios) or diverge (very small changes in scenario parameters lead to vastly different futures).

The analysis revealed that there are a large number of factors in addition to quantitative validation statistics that contribute to model uncertainty. Many of these factors are often taken for granted in traditional uncertainty assessments, but provide significant insight when re-introduced to the assessment. The combined uncertainty data-dictionary and qualitative interview method presented here provides a framework for the collection of these data. The ranked-variable fuzzy set is an effective tool for the collection of *holistic* modeller certainty information that allows the broader contextual issues to be actively included in the interpretation *alongside* traditional validation statistics; the resulting network makes a very useful discussion tool.

The approach presented here was designed to be flexible so that differences in perceptions can be integrated and data included rather than excluded. Whilst the fuzzy quantification approach helps to address differences in perception between modellers into a more comparable index, differences in inter-modeller perceptions will always influence any manipulation of the quantified results. However, there are opportunities to further refine the variable-to-variable network in collaboration with the modellers themselves. A reflexive approach using the existing network as a tool for discussion will aid modellers to better understand the certainty that other modellers give to the data for which they are responsible. A modeller workshop would provide an ideal opportunity and help reduce inter-modeller differences in both typologies and variable classification.

Sensitivity analysis[7] of the interlinked V2V network would also help in exploring the responses of the IAP as a whole to a range of input scenarios and help to quantify which areas of the network were most sensitive to small deviations in input parameters. By combining this type of network information with the uncertainty V2V network it would be possible to identify the nodes with greatest risk: where modeller confidence is low yet the sensitivity of the rest of the system to that node is high.

Furthermore, it should be noted that a single model has been used for each sector. Whilst alternative models exist for each of the IAP sectors, the selected models provide the best solution in terms of model accuracy and run-time trade-offs for this particular implementation. As such we do not explore the impacts of model selection uncertainty here; including an ensemble of models for each sector within the IAP would address this (e.g. Manning et al., 2009; Breuer et al., 2009).

Time, licensing, costs, resources, skills and experience were all identified as factors external to the scientific method that influence the level of certainty achievable by the modelling approach. In reflecting on these it is important to be aware that they are not examples of

[7] Note: a sensitivity and scenario analysis of the IAP is reported in Deliverable 4.4.

science being done badly. Repeatable methods are followed, hypotheses tested and validation datasets are checked and reported on. Nor should the issues raised be seen as simply a case of modellers complaining. There will always be more that can be done with more time and resources and pragmatic factors will affect not only the confidence that modellers have in their own models ("expert certainty") but also the level of confidence that *it is possible to have* with their models. Latour and Woolgar (1979) argue that factors such as these are often left out of the discussion of the scientific/modelling process. Doing so gives an appearance of a greater separation between the modeller and the model, than there is in practice; and a greater air of certainty as a result. The holistic uncertainty approach taken in this paper aims to add these pragmatic factors back in by exposing the factors that contribute to uncertainty in a way that allows them to be taken into consideration when making decisions. By reflecting on the available data and the modeller's decisions and reasoning we can contextualise validation statistics with reference to overall holistic certainty that a variable matches the real world value it is intended to.

The research presented here presents a number of opportunities for extending the IAP in the future to communicate uncertainty information to the IAP users. This includes: (i) simple presentation of the V2V confidence maps; (ii) tooltips over variables on the IAP which provide the user with the certainty information from the uncertainty data dictionaries; and (iii) an "uncertainty mode" where all variable names and input sliders are coloured by their level of expert certainty or a combination of these. This work, coupled with stakeholder workshops and interviews would help to explore the extent to which the holistic understanding of uncertainty contributes to better understanding of the modelling process, and aids the user's decision-making experience.

5. Conclusions

Uncertainty is unavoidable, but decisions must be made and environmental models present one of the few methods that allow decision-makers to explore projections of the future. The CLIMSAVE IAP supports decision-makers by providing a better understanding of cross-sectoral interactions so that they are aware how adaptation decisions made about one sector have potential consequences for other sectors. However, models are only representations of reality, and we can have greater confidence in some aspects of them than others. Ignoring this uncertainty is not an option. However, by exploring multiple scenarios and by classifying and exploring uncertainty in conjunction with the model developers both scenario and model uncertainty can be addressed. By doing so we can ensure not only that the modelling system itself improves, but that the decisions based on it can draw on the best available information: the modelled impacts themselves, and a holistic understanding of the uncertainty involved in their creation.

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ANNEX 3: Quantitative uncertainty analysis

Uncertainty analysis of an Integrated Assessment Platform for European climate change

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Introduction

The extent to which the Earth's climate will change in coming decades is uncertain, and the impacts of any change are more uncertain still (Karl & Trenberth, 2003; Parry et al., 2004; Pereira et al., 2010). Not only is the climate system itself impossible to predict precisely, but the human and natural systems it impacts upon are highly complex in their own right (Rial et al., 2004; Stainforth et al., 2005). Furthermore, all of these systems interact strongly with each other, so that small uncertainties about one can have very substantial and general consequences for the reliability of predictions about others (e.g. Pielke et al., 2002; McMichael et al., 2006; Lavorel et al., 2007; Dawson et al., 2011).

Nevertheless, it is precisely because the impacts of climate change depend to some extent upon the actions (and reactions) of human populations and institutions that accurate assessments of their magnitude are needed. Attempts to lessen, mitigate and respond to climate change are global political priorities (nominally at least) and social, economic and environmental necessities (Parry et al., 2007; Anderson & Bows, 2011). Decision-makers therefore require accessible and accurate information about the effects of climate change, and about the limitations of our knowledge of these effects (Polasky et al., 2011).

A large number of models have been developed to explore the likely course and magnitude of climate change, and many of these also illuminate its consequences (IPCC, 2013). However, individual models tend to focus on single physical or socio-economic processes that are implicitly assumed to operate in isolation, neglecting the many feedbacks that occur between these processes in reality (Warren, 2011). An increasingly used method of tackling this problem is to combine models in large ensembles or in integrated assessment platforms (IAPs) (e.g. Bollen et al., 2010; Rowlands et al., 2012; Ibáñez et al., 2013). The IAP developed in the CLIMSAVE project is one example of this, combining 10 different meta-models focused on distinct sectors or processes (Harrison et al., 2013). Because of their scope, IAPs of this kind can be used to explore impacts and adaptation options under climate change (Füssel, 2010; Patt et al., 2010). The CLIMSAVE IAP is specifically intended to allow assessment of cross-sectoral impacts and vulnerabilities across Europe.

However, where disparate models are combined, particular attention must be paid to the reliability of the results that are generated. One major source of potential errors and uncertainties in these results is the design of models themselves – the underlying data used, the parameters that are included, the treatment, simplifications or assumptions concerning the interactions of these parameters, and so on (Murphy et al., 2004; Collins et al., 2006). It is crucial to understand these model-based uncertainties in any application, but especially where they may combine with one another in previously unconsidered and potentially unpredictable ways (van Vuuren et al., 2009). Where simplified (and hence potentially less accurate) meta-models are combined, as in the case of the CLIMSAVE IAP, investigation of model-based uncertainty becomes an even greater imperative. As a result, a range of methods for quantifying model uncertainties have been established (e.g. Smith et al., 2009; Stainforth et al., 2005) and some of these have been applied to the CLIMSAVE IAP (Dunford et al., in review).

Another class of uncertainties relates to assumptions about future climatic, economic or social change. Such assumptions are widely made in the development of scenarios intended to describe plausible conditions at some future point in time (Mote et al., 2011). These are required where models seek to address the impacts of climate change or, especially, potential mitigation or adaptation options, because the state of interacting climatic and human systems cannot be accurately predicted (Moss et al., 2010). Consequently, scenarios themselves incorporate substantial uncertainties about their plausibility, representativeness, and robustness to alterations in the conditions they describe (although it must be remembered that scenarios are intended to be exploratory rather than predictive). These uncertainties are more difficult to identify and quantify but, once again, a number of methods have been established and used in the CLIMSAVE project (Mote et al., 2011; Dunford et al., in review).

The CLIMSAVE IAP, in common with other similar model combinations, therefore has a number of important sources of uncertainty that affect the confidence with which its results can be considered. In this case, it is crucial to understand these uncertainties because the IAP is intended to provide policy-makers and others with a tool for investigating impacts of climate change and potential political, economic and social responses to minimise vulnerabilities (Harrison et al., 2013). As a result, a rigorous investigation has been performed to allow the quantification of uncertainties in the input parameters used by the CLIMSAVE meta-models (Dunford et al., in review). A separate sensitivity analysis has quantified the effect of variations in each single parameter on IAP output indices (Kebede et al., 2013).

In this paper, we use the knowledge gained by the above work to investigate the aggregate uncertainties in IAP outputs caused by uncertainties in input parameters (and therefore by underlying model and scenario uncertainties). We assign values to input parameters to explore joint parameter uncertainty space, and summarise IAP output results using a small number of indices operating at different spatial scales, intended to capture the range of impacts of climate change on human and natural systems. We then perform a sensitivity analysis to identify the parameters that have a particularly strong influence on output uncertainties, and which, therefore, play the greatest role in limiting the accuracy of model predictions. Our findings allow us to quantify uncertainty about the impacts of climate change under different socio-economic scenarios and to determine where future work on decreasing parameter uncertainty can best be targeted. We are then able to describe the implications of the findings of the CLIMSAVE IAP given their inherent uncertainties, and discuss their relevance to the real climate system and attempts to limit, mitigate or respond to climate change.

Methods

The Integrated Assessment Platform (IAP)

The CLIMSAVE IAP is intended to provide a powerful but user-friendly method for assessing the cross-sectoral impacts of, and potential adaptation to, climate change in Europe (Harrison et al., 2013). It incorporates 10 meta-models, each of which has a different focus within the over-arching aim of exploring the possible future development of interacting climate, human and natural systems. Full details of the IAP and its component meta-models are given in other Deliverables.

The IAP includes a range of climate change scenarios and four socio-economic scenarios which were developed by stakeholders in facilitated workshops (see Deliverables 1.4 and 3.3). These scenarios are designed to span the range of uncertainties relating to emission scenarios, climate sensitivities and climate models, and to be to be representative of a large number of different possible futures. The socio-economic scenarios were named “We are the World”, “Icarus”, “Should I Stay or Should I Go” and “Riders on the Storm”. A total of 89 parameters define each scenario (not all are relevant to our uncertainty analysis), and values are set independently in each. However, these values can be varied freely by users of the IAP, with possible, credible and most likely values provided for guidance in each case (see below). The IAP can be run through a web-based interface, or in batch mode by the provision of files including complete parameterisations of the scenario(s) being used. The latter approach is adopted here.

Parameter sampling procedure

The work presented here depends upon previous analyses presented in Dunford et al. (in review; see Annex 2) and Kebede et al. (2013; Deliverable 4.4). The former study investigated model and scenario uncertainties to allow a quantification of input parameter uncertainties, and the latter investigated the sensitivity of IAP output indices to variations in individual input parameters. As a result of these, information about the ranges of values taken by input parameters, and the importance of these ranges, was available to our analysis.

The ranges of parameter values incorporated information on data, model and scenario uncertainties, and were scenario-specific. In addition to ‘possible’ intervals within which each parameter’s values were feasible under each scenario, ‘credible’ ranges were provided to represent the most probable range of values, along with a single ‘central’ value that represented the most probable single value (see Deliverable 2.4 for an explanation of the input sliders and the default (central) value, credible range and possible range). In consultation with modellers and relevant experts within the CLIMSAVE project, these ranges and values were converted to probability density functions (PDFs) for the purpose of parameter sampling. First, we made assumptions about the probabilistic interpretation of the values available to us. These assumptions were: (a) that the central (‘most likely’) value of a parameter’s range represented the mode of its PDF; (b) that the credible range of a parameter spanned most of the PDF, quantified here as approximately 90%; and (c) that the possible range of a parameter (now set to approximately 10% of the PDF) gave the limits of the PDF, so that values outside this range could not be taken.

Beta distributions were chosen to represent parameter PDFs because of their flexibility, compatibility with the above assumptions and limited range, meaning that truncation was not required. They have also been used in previous quantifications of uncertainty (e.g. O’Hagan, 1998; Heath & Smith, 2000) and were judged to provide a good approximate representation of the underlying (and not fully known) uncertainties in the physical processes being modelled. Separate distributions were fitted to each parameter in each scenario, using an online tool developed for fitting beta distributions to observational data (AAHS, 2013). Fits were calculated on the basis of the mode (the central parameter value) and the closest of the 5% or 95% limits (the lower or upper credible range limits), both of which were scaled so that the possible range spanned the interval [0, 1]. This ensured that all assumptions were satisfied, although it was not possible to precisely define the range of probabilities within the credible ranges, especially where distributions were strongly asymmetrical and skewed (although the beta distribution is adept at representing skewed data, its own properties make it unable to provide an exact match in all cases, particularly where data are asymmetrically distributed around a mode near the centre of the possible range). Nevertheless, because the given probabilities were either symmetrical or had modes that diverged substantially from the middle of the possible range, beta distributions provided good fits, with superior adherence to the probabilistic interpretation of supplied parameter ranges than other distributions could have provided.

A subset of the 89 parameters used by the IAP were relevant to our analyses, and we defined this subset as follows. First, because we were concerned only with predicted impacts of climate change, we discarded parameters that only had relevance for mitigation. Then, using the results of the previously-conducted sensitivity analysis (Kebede et al., 2013; Deliverable 4.4), we discarded parameters found to have insignificant impacts on model outputs. This left us with 21 parameters that were both relevant to climate change impacts and had a significant effect on model outputs.

Once PDFs were established for each of the four scenarios and parameter selection was complete, samples were taken randomly from every PDF. The number of samples varied between scenarios because different analyses were planned in each case (see below) and because time and computing constraints meant that the number of samples had to be kept to a minimum. Where quantification of the uncertainty in model output indices was the sole objective of the analysis (in the Icarus, Should I Stay or Should I Go and Riders on the Storm scenarios), 50 samples were taken from each parameter to ensure a basic exploration of the range of each parameter's PDF. When a sensitivity analysis was planned subsequently to the uncertainty analysis (in the We are the World scenario), 250 samples were taken from each parameter so that the form of each PDF was better represented, allowing the individual and interactive influence of every parameter to be investigated.

Once these initial samples were taken, a Monte Carlo resampling procedure using the soboljansen function in R package sensitivity (Jansen, 1999; Sobol, 2007; Saltelli et al., 2010; Pujol et al., 2013) was used to generate a series of model parameterisations that systematically explored joint parameter uncertainty space. This step was necessary because a straightforward combination of the initial samples would have produced model parameterisations that were clustered in certain areas of joint parameter space. The resampling procedure orders individual samples on the basis of previously sampled points, so ensuring that parameter values are distributed according to joint, rather than individual, parameter probabilities, allowing an accurate assessment of how uncertainties interact and influence model outputs (Saltelli et al., 2010; Berhenne et al., 2011). The method selected has a (relatively low) computational cost of N(k+2), where N is the number of initial samples and k the number of parameters included in the analysis, so that we required 250*23 = 5,750 IAP runs with different parameterisations for the We are the world scenario and 50*23 = 1,150 IAP runs for each of the remaining three scenarios. The total 9,200 parameterisations were run through the IAP in batch files for the 2050s timeslice, with parameters that were not included in the analysis being held at their default (central) values.

Analysis of results

Each IAP run produced results expressed in 174 output metrics, at the scale of individual cells across the whole of Europe. In order to make the analysis of results manageable and easily interpretable, we focused on six main metrics that illuminate the predicted sectoral impacts of climate change, and which formed the basis of the previous sensitivity analysis: the food available per capita, land use diversity, land use intensity index, people flooded by a 1 in 100 year flooding event, water exploitation index and biodiversity vulnerability index. We expressed these metrics at the national and European level by averaging up from the cell level, and assessed uncertainty in the results visually (by plotting distributions of the metrics) and via the standard deviations of the values taken by each metric. Where we performed a subsequent sensitivity analysis to identify the input parameters with the greatest contribution to output uncertainty, we again used the soboljansen R function, to estimate Sobol indices for each parameter (Jansen, 1999; Sobol, 2007; Saltelli et al., 2010). These indices characterise the sensitivity of the output metrics to the input parameters, singly and in combination, and so highlight the main sources of observed uncertainty. The calculation depends upon the sampling procedure outlined above.

Results

The analysis presented here generated a large number of results, some of which will be subject to further analysis in the future. Here we present a summary of the main findings of the uncertainty analysis for three CLIMSAVE scenarios – We are the World, Riders on the Storm, and Icarus. Results are expressed at the European and national level.

European results

The European results show the uncertainties in the six selected model output metrics at the European level (with values for each IAP run averaged across all modelled grid cells). They therefore indicate which of the metrics and scenarios have the highest levels of uncertainty associated with them. Plots of the values taken by each metric in each scenario are shown in Figures 1a-f.

These plots show that uncertainties in all metrics and scenarios are substantial, with values taking wide ranges and often bi- or multi-modal distributions. There are also some clear differences between the scenarios, with some producing considerably smaller uncertainty ranges for particular metrics than others (although no scenario is consistently less uncertain than the others). In terms of metrics, the land use diversity index has the lowest levels of uncertainty associated with it, even though it is clearly related to the intensity index, which has relatively high uncertainty levels. However, it is difficult to compare indices operating on different scales, and the significance of the observed uncertainty levels are likely to depend upon the application for which results are generated.

Nevertheless, despite broad and overlapping uncertainty ranges, results for some metrics have clear modes, small standard deviations, and distinct forms under different scenarios. For instance, it remains possible in almost every case to rank scenarios by the values of metrics that they produce even after taking account of uncertainty. This suggests relationships between scenario assumptions and model outputs that are robust to model and scenario uncertainty.

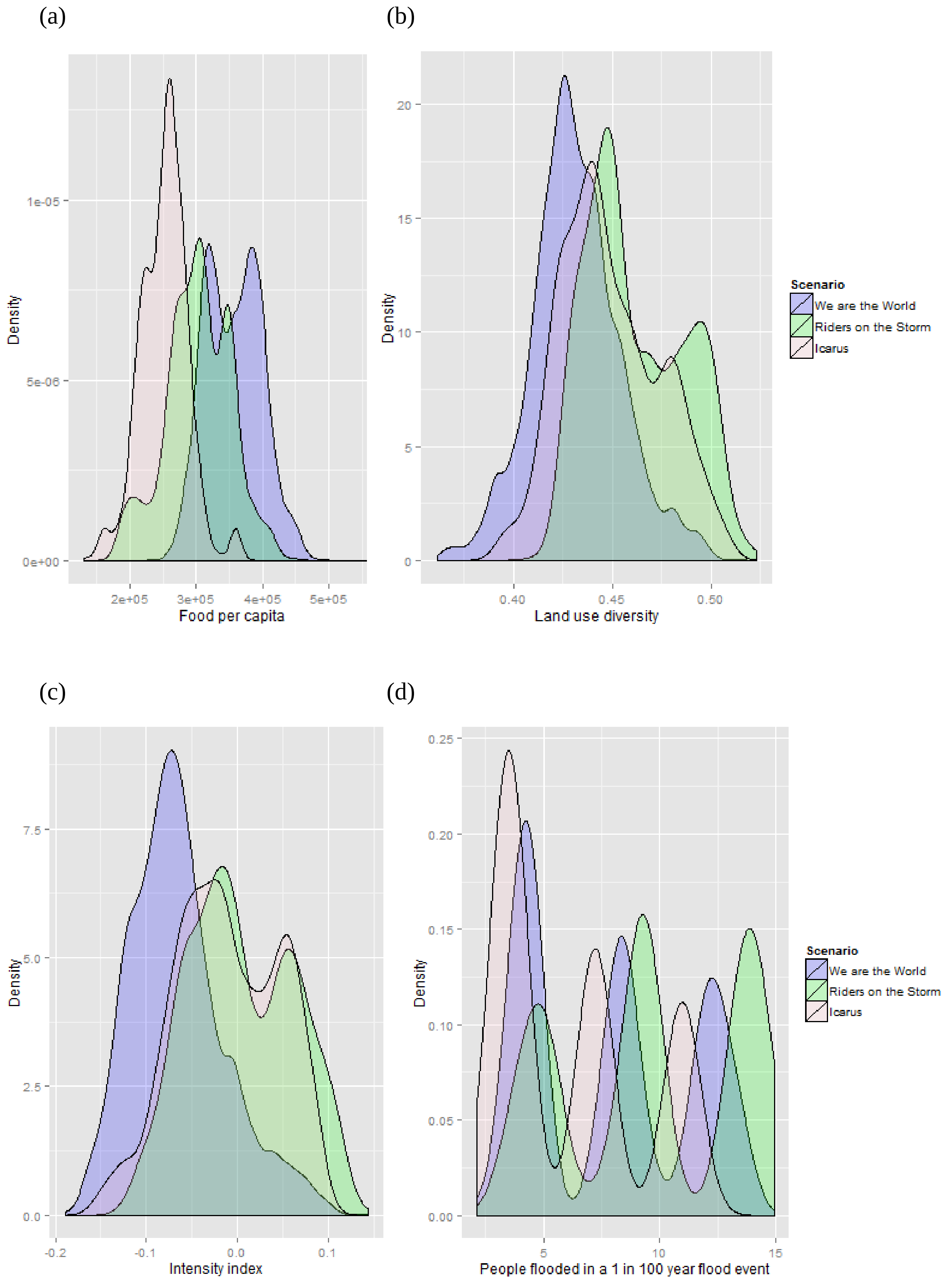


Figure 1: Uncertainties in: (a) mean food per capita values; (b) mean land use diversity values; (c) mean intensity index values; and (d) mean number of people flooded in a 1 in 100 year flooding event.

(e) (f)

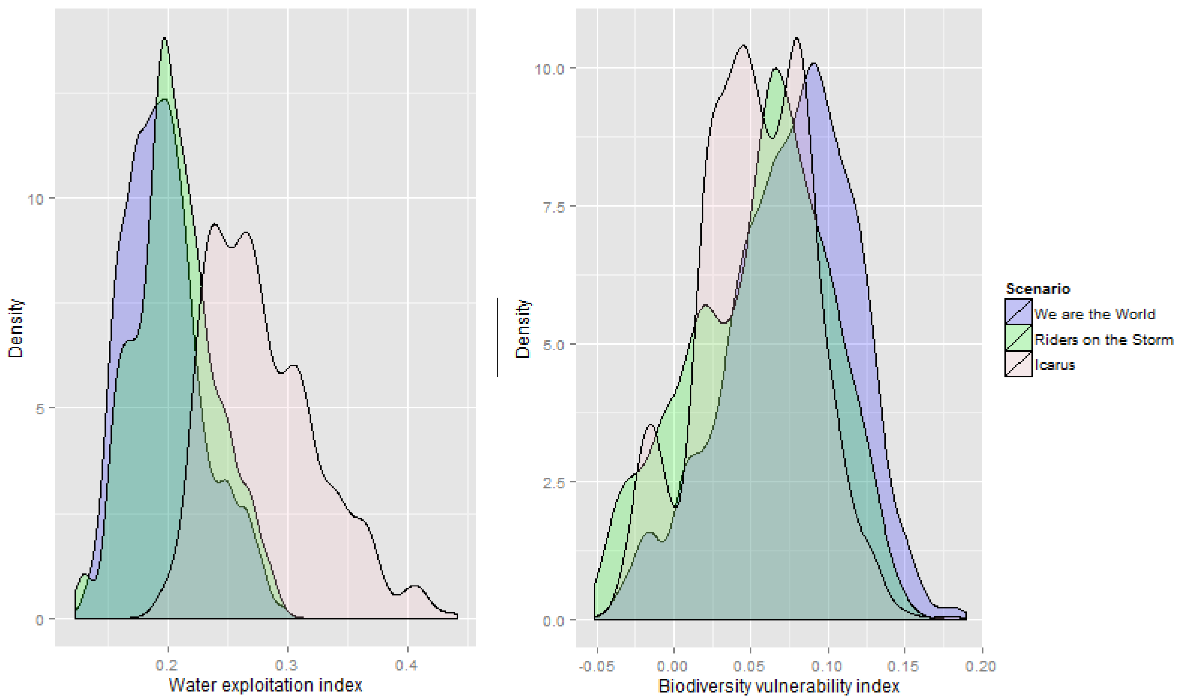
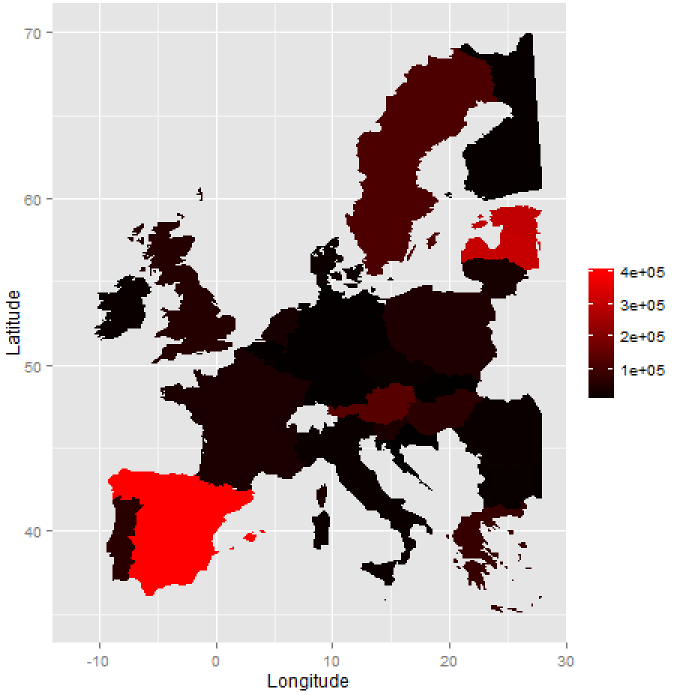


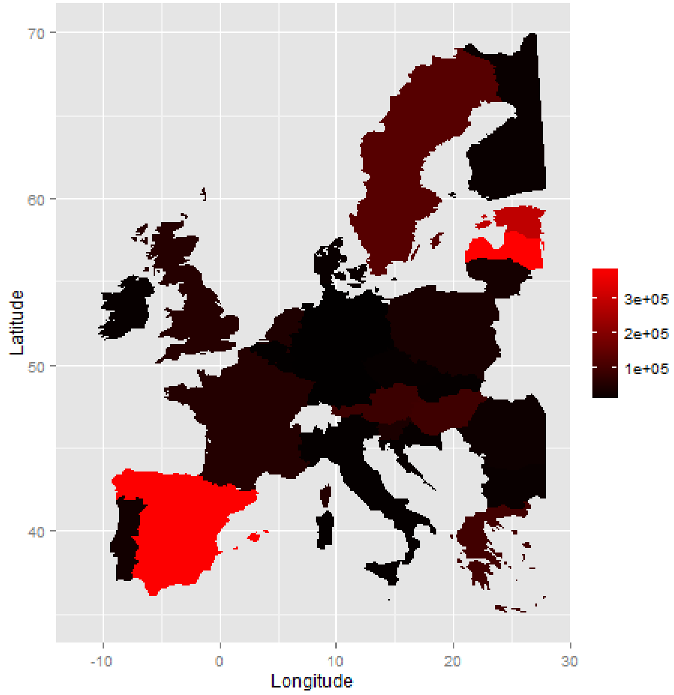
Figure 1 continued: Uncertainties in: (e) mean water exploitation index values; and mean biodiversity vulnerability index values.

National level results

National-level results are generated in order to identify countries and regions where uncertainties are largest, and therefore where model results are least reliable. Because of the extra information incorporated in these results, they are presented separately for each scenario and metric. Uncertainties associated with each of the six metrics averaged at the national level are presented in Figures 2a-f, with uncertainties expressed as the standard deviation of the values taken by the metric in each case.

National-level results show that all three scenarios are broadly consistent in the location, if not the size, of their uncertainties. In general the greatest uncertainties occur in Spain or France and eastern Europe, while central Europe and the UK have the lowest levels of uncertainty. The extremely high levels of uncertainty associated with Malta in the number of people flooded in a 1 in 100 year flood event are also found in all scenarios. The considerable differences that exist between countries, however, mean that many countries have substantially less uncertainty associated with their results than was suggested by the European results above, and so model outputs are more reliable than would be thought on the basis of European results alone.





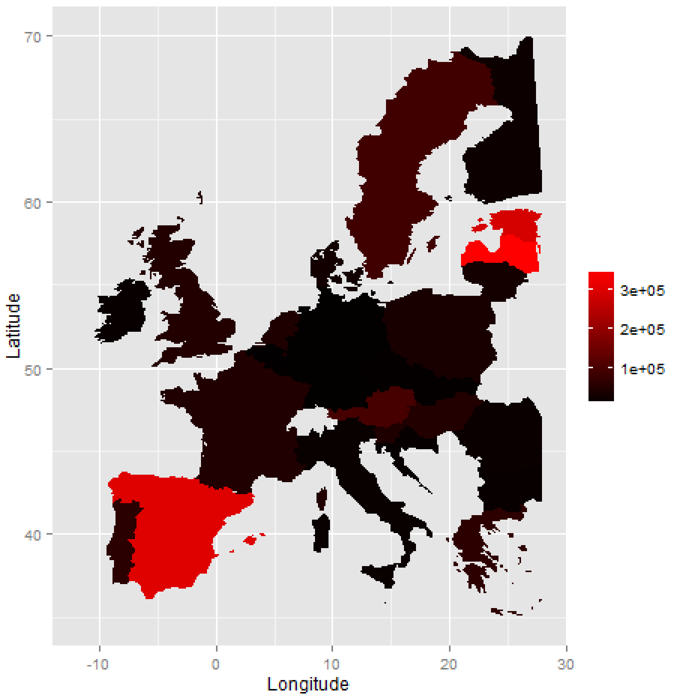
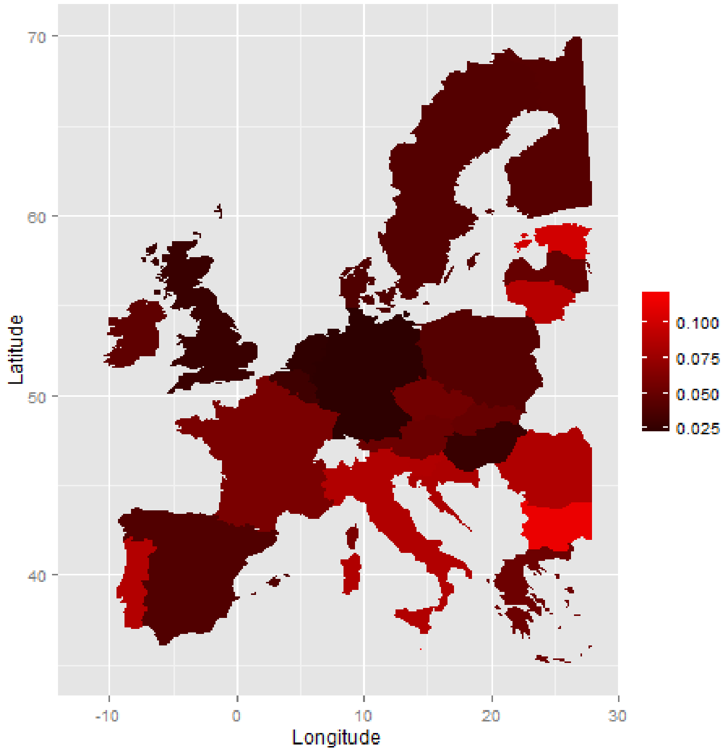
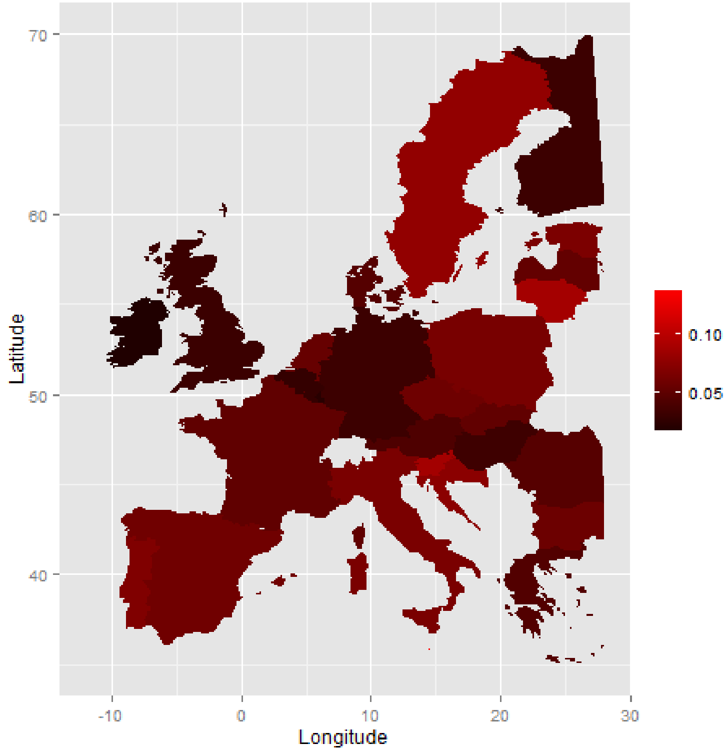


Figure 2a: Uncertainties in food per capita values at the national level in the We are the World (top left), Riders on the Storm (top right) and Icarus (bottom left) scenarios.





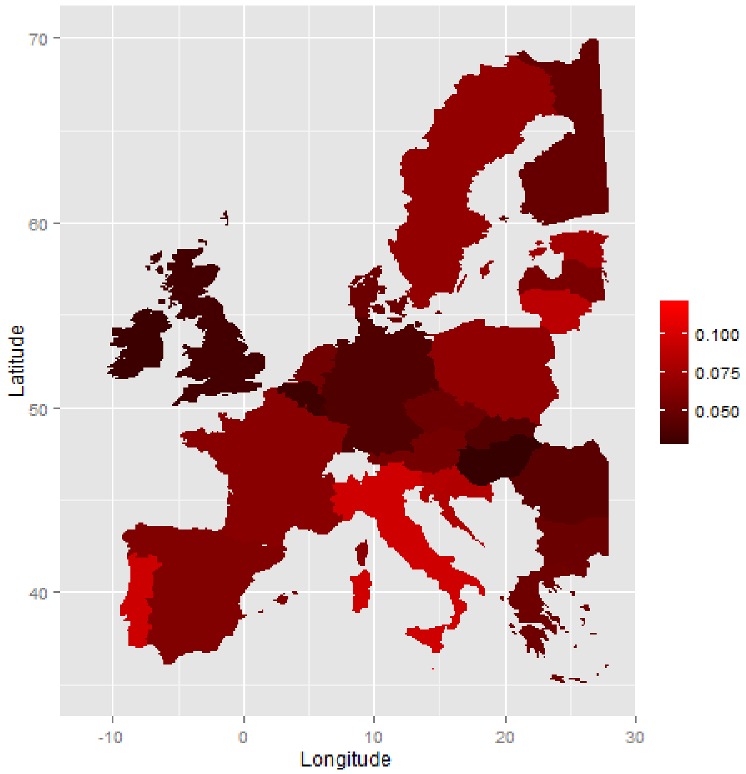
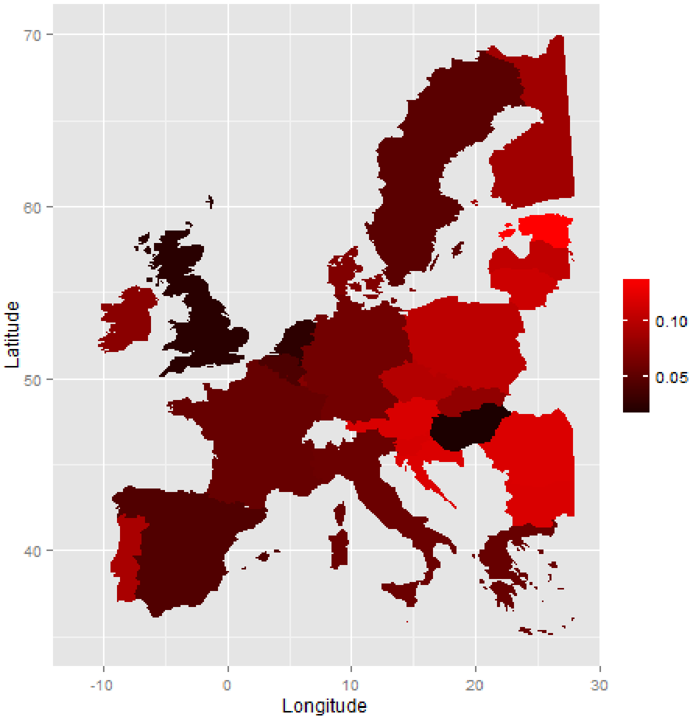
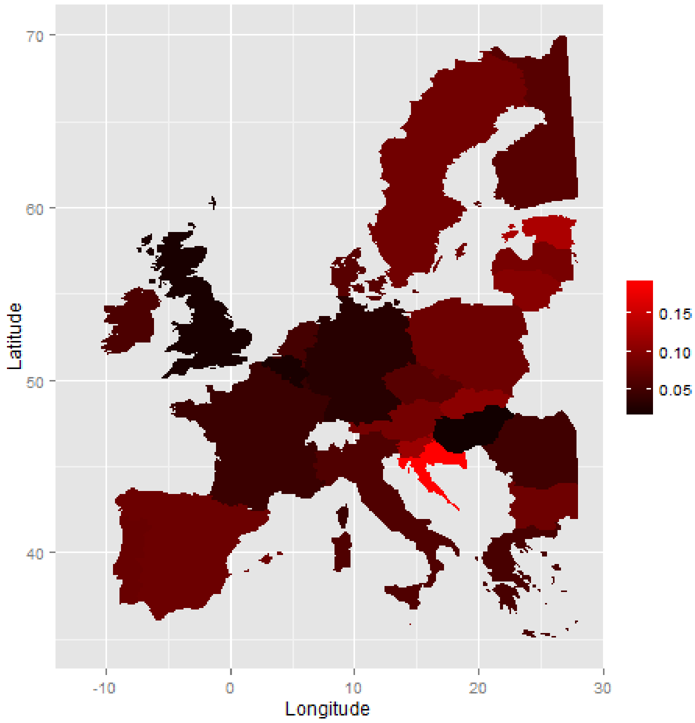


Figure 2b: Uncertainties in land use diversity values at the national level in the We are the World (top left), Riders on the Storm (top right) and Icarus (bottom left) scenarios.





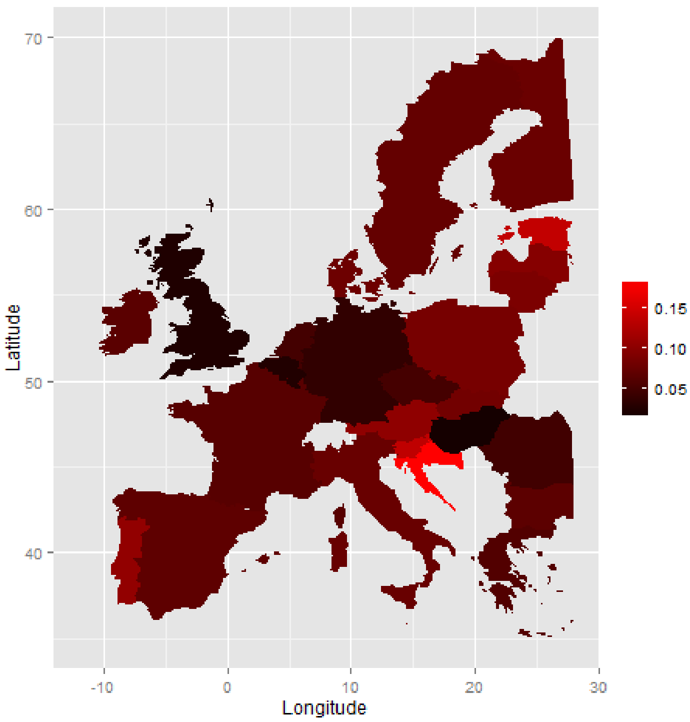
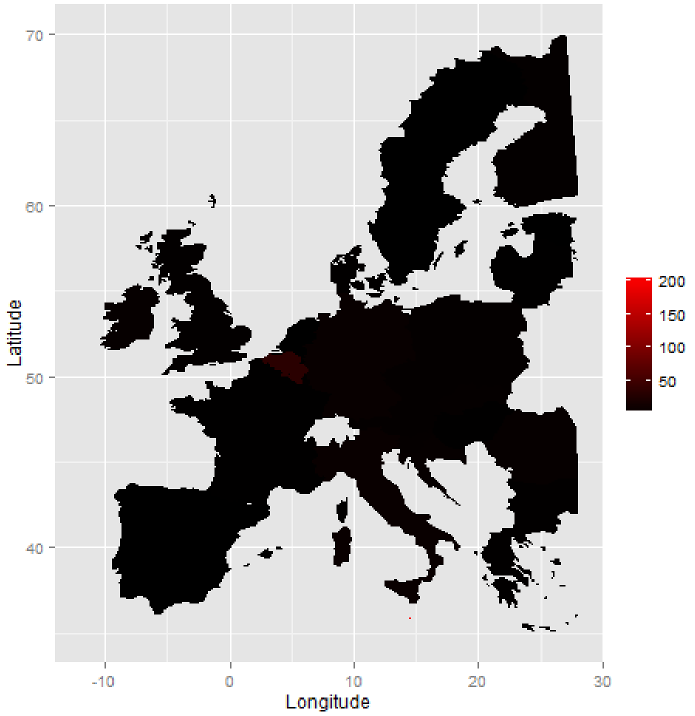
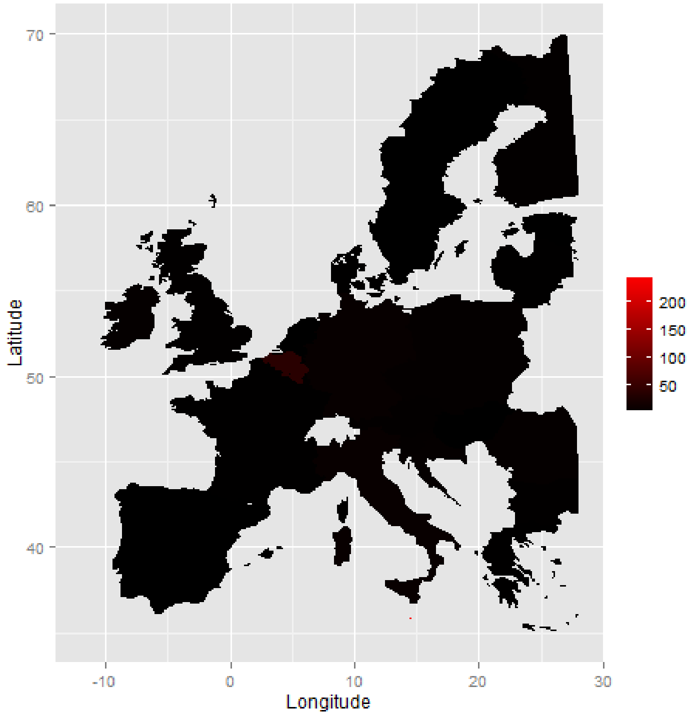


Figure 2c: Uncertainties in the intensity index at the national level in the We are the World (top left), Riders on the Storm (top right) and Icarus (bottom left) scenarios.





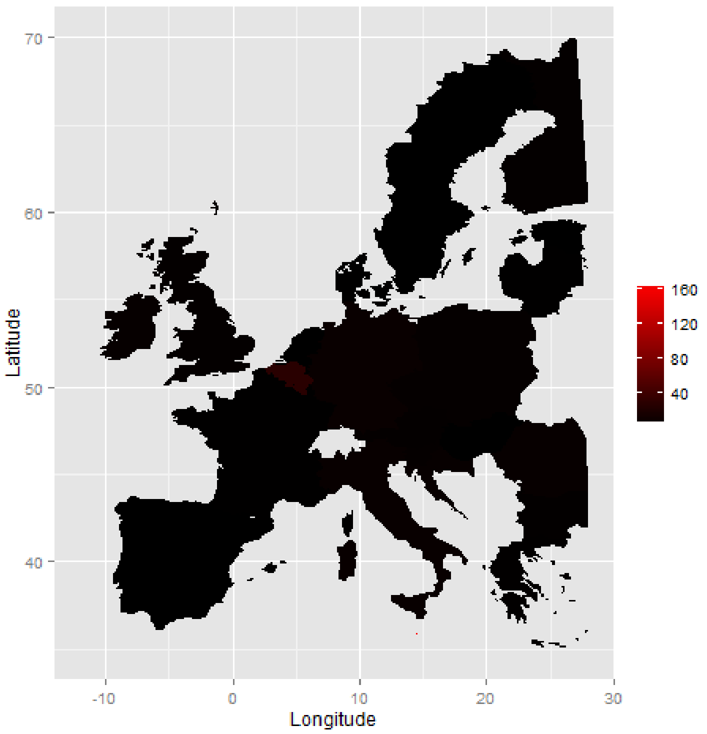
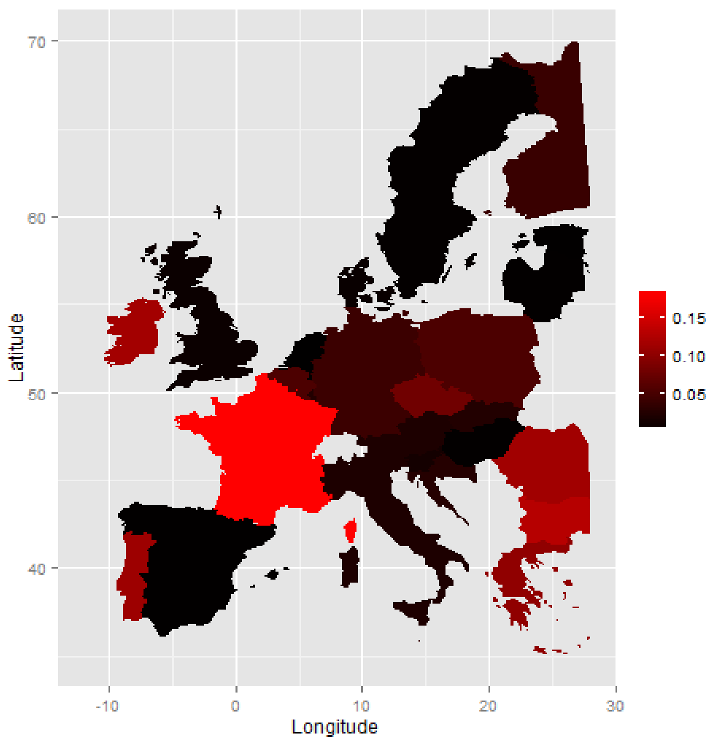
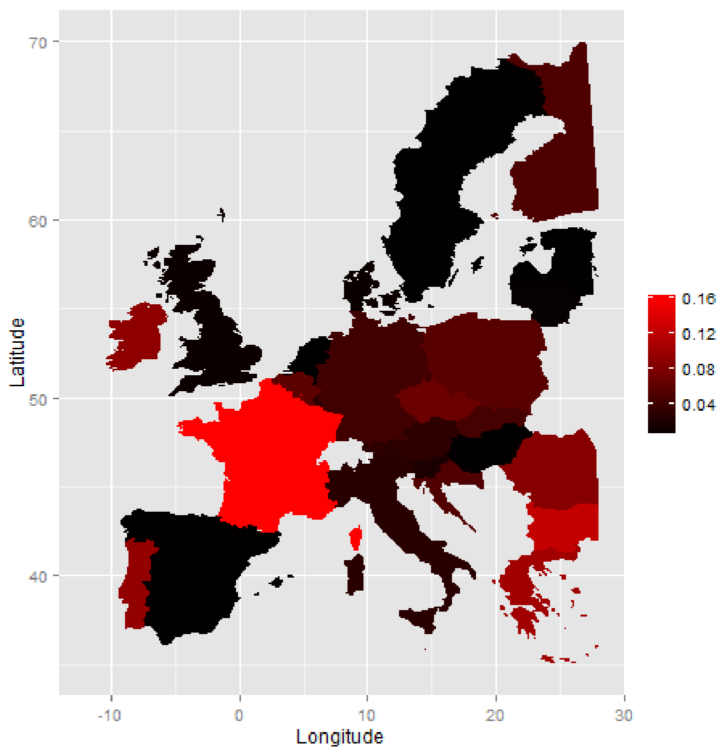


Figure 2d: Uncertainties in the number of people flooded in a 1 in 100 year flood event at the national level in the We are the World (top left), Riders on the Storm (top right) and Icarus (bottom left) scenarios. Note that uncertainty is extremely high in Malta in every case, and makes variations between other countries difficult to detect.





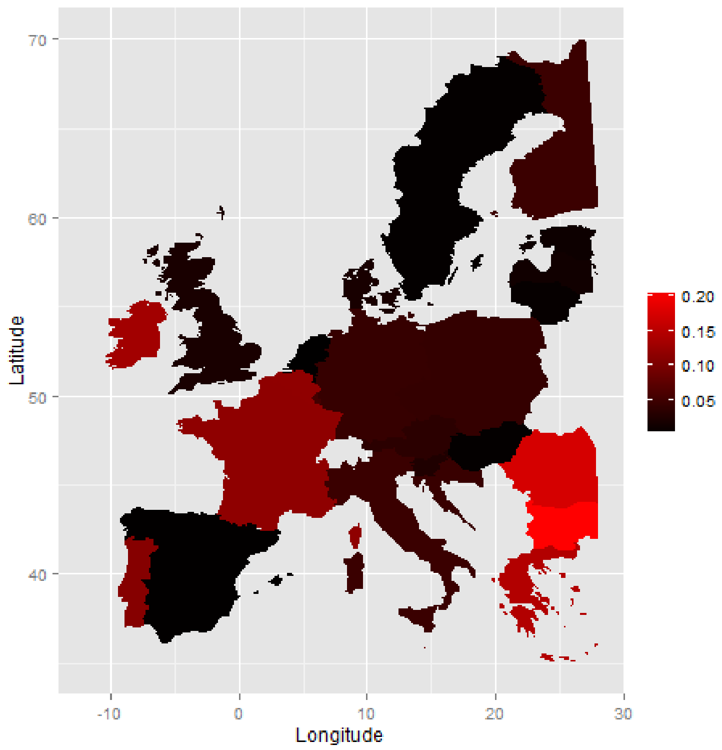
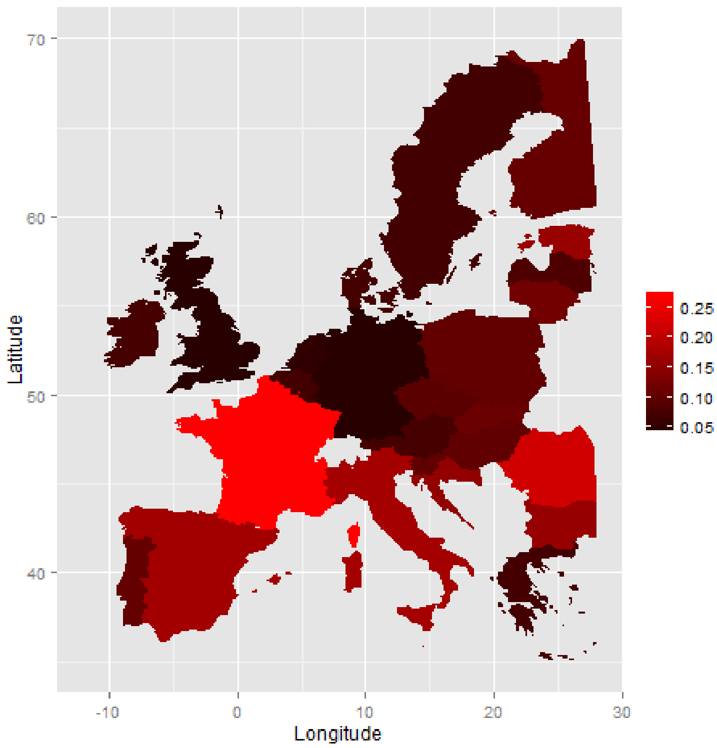
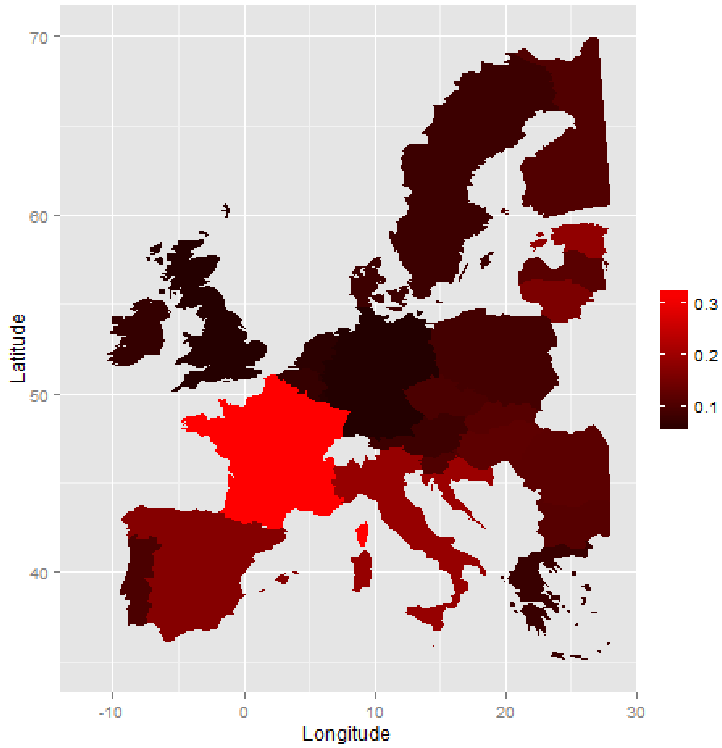


Figure 2e: Uncertainties in the water exploitation index at the national level in the We are the World (top left), Riders on the Storm (top right) and Icarus (bottom left) scenarios.





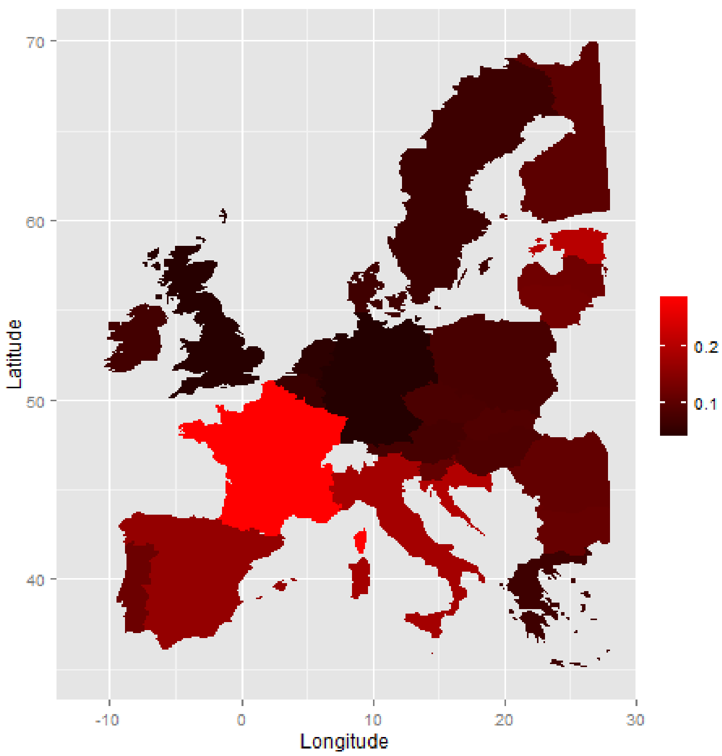


Figure 2f: Uncertainties in the biodiversity vulnerability index at the national level in the We are the World (top left), Riders on the Storm (topright) and Icarus (bottom left) scenarios.

Discussion

The limited set of results presented here captures the uncertainties in six principal outputs of the CLIMSAVE IAP. These outputs concern projected impacts of climate change on different sectors, and represent measures that are likely to be of particular interest to policy-makers and other users of the IAP. As such, their robustness to uncertainties in model inputs is very important to assess.

Our results show considerable uncertainties in each of the six chosen metrics, which have the potential to dramatically alter implications for climate change impacts, vulnerabilities and adaptation. The results of the CLIMSAVE scenarios are not reliably distinct from one another in either the output values they produce or the spread of these values. This suggests that the socio-economic differences assumed between scenarios are not influential enough to ensure distinct climatic outcomes in this modelling framework.

However, each scenario does produce clear and partially separate distributions of output values at the European level (although these are not always unimodal). This demonstrates that data, model and scenario uncertainties do not entirely erode differences in the outcomes of different scenarios, and that it may be possible to predict these outcomes, given scenario assumptions, with a defined level of confidence. It is also apparent that none of the scenarios is inherently more uncertain than the others, and each has different implications for the uncertainties in different model outputs. It is likely that certain aspects of the scenarios could be linked to particular impacts of climate change as a result.

Uncertainties expressed at the national level are more informative about model performance and, perhaps, knowledge of the physical processes that mediate between socio-economic factors (as expressed in the scenarios) and impacts of climate change. These uncertainties show that there is considerable range in the reliability of model results between countries, but also that there is considerable agreement between scenarios about where the greatest uncertainties are found. These broad findings suggest either that fundamental issues concerning knowledge (in terms of data or modelling) about particular countries exist, or that the impacts of climate change are genuinely more uncertain and less reliably linked to scenario assumptions in these countries. The consistently and extremely high levels of uncertainty about the impacts of flooding in Malta, for instance, suggest a failure relating to data or modelling of processes in that country. Large uncertainties for France and Spain, in contrast, suggest a genuine lack of predictability in the impacts of climate change here, perhaps as a result of strong sensitivity to the climatic and socio-economic assumptions made in the scenarios.

National-level uncertainties also illustrate that the CLIMSAVE IAP is a robust and informative tool for exploring certain impacts of climate change in certain regions. For the six metrics considered here, uncertainty is consistently relatively low in central and northern Europe. While differences between scenarios are also not very great in these areas, those that do occur can be treated with confidence. This also demonstrates the need for users to take account of locational and sectoral uncertainties when using the IAP, and the value of a thorough uncertainty analysis.

Despite the fact that our findings allow us to draw a number of conclusions about the effects of data, model and scenario uncertainties, it is important to bear in mind that they do not capture all of the potential errors and uncertainties in model outputs. In particular, the use of simplified meta-models in the IAP (which is necessary to enable modelling across the spatial and sectoral range covered by the IAP) introduces assumptions and, potentially, inaccuracies that may not be recognised or apparent (Ackerman et al., 2009). More specialised models are likely to treat individual processes more robustly, and may generate quite different results (van Vuuren et al., 2009). Furthermore, it is possible that unexplored assumptions are made across a suite of models or meta-models, and that these introduce biases into results (Masson & Knutti, 2011). An uncertainty analysis of the kind presented here depends upon accurate identification and quantification of underlying uncertainties relating to such assumptions.

Although uncertainties are inevitably large and difficult to fully describe in modelling approaches such as this, it is important that they are investigated. Decisions about climate change must be made, even in the face of uncertainties about its course, magnitude and effects, and methods to reduce or quantify these uncertainties are therefore extremely valuable (Polasky et al., 2011). The investigation of uncertainties in the CLIMSAVE IAP not only allows more confident, effective use of the tool itself, but suggests a number of avenues for further research and helps to illuminate the real-world processes that have been modelled.

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