Integrated assessment approach

Deliverable D3.1

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Timothy R. Carter[1], Mark D.A. Rounsevell[2], Stefan Fronzek[1], Paula A. Harrison[3], Ian P. Holman[4], Nina K. Pirttioja[1]

[1]Finnish Environment Institute (SYKE), Finland
[2]University of Edinburgh, UK
[3]University of Oxford, UK
[4]Cranfield University, UK

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

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Preface

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

This report describes the integrated modelling framework adopted in IMPRESSIONS. It catalogues the models to be applied in the project, details model characteristics, dependencies and linkages and outlines different types of planned model analysis. In so doing, it also addresses the three main tasks outlined in the description of work (DoW):

1. Development of a multi-scale, integrated assessment approach;
2. Development of guidance and protocols to facilitate implementation of the multi-scale, integrated assessment approach; and
3. Representation of the adaptation process in the climate change impacts, adaptation and vulnerability models adopted in the project.

Much of the information received and many of the decisions taken that are reflected in this document were obtained at two modelling workshops held in London (April 2014) and Pisa (September/October 2014) as well as at General Assembly sessions in Oxford (January 2014) and Barcelona (January 2015). These meetings were attended by representatives of all partner organisations and modelling groups, to which the authors express their great appreciation. However, any errors or misrepresentations are the responsibility of the author team alone.

Summary

This deliverable describes the overall modelling methodology for the IMPRESSIONS study. It comprises a multi-scale, integrated approach to assessment, focusing on case studies at global, European, national and sub-national scales. A conceptual framework is presented that is a dynamic variant of the DPSIR framework developed by the European Environment Agency. This explicitly accommodates adaptive management through a time dependent and iterative approach incorporating system feedbacks. Its purpose is to establish a structure within which the model applications are undertaken, and it facilitates consistency of modelling across the various case studies.

More than 20 models are being applied in IMPRESSIONS for exploring climate change impacts, adaptation, vulnerability and mitigation. The modelling strategy comprises six actions that all modelling groups need to consider in IMPRESSIONS. These are:

1. **Cataloguing of models**, which has involved describing model characteristics (through a questionnaire), inputs and outputs (via data dictionaries), model linkages, and the treatment by models of adaptation.
2. **A review of past studies**, which scans past work with the model that might offer insights about model sensitivity and fitness for purpose under climate change, especially at the high-end of climate projections.
3. **Sensitivity analysis**, describing simulations, with simplified model assumptions, that explore responses of important model outputs to a range of key input variables. This offers a method of testing model sensitivity to a plausible range of future conditions comparable to those found in the scenario analysis (see below). It also offers an opportunity to compare model outputs for the same range of driving variables using impact response surfaces.
4. **Scenario analysis** is the core activity involving impact model projections through to 2100. It involves the application of climate and socio-economic scenarios defined in Work Package (WP) 2 based on the RCP/SSP global scenario framework, and is also guided by the adaptation and mitigation pathways developed in WP4. This analysis is both informed by (e.g. through model behaviour under high-end forcing) and feeds back into (e.g. by defining key driving variables) the sensitivity analysis.
5. **Likelihood of impacts** involves an advanced sensitivity analysis for key driving variables with more realistic model assumptions than in (3) above. The impact response surfaces generated by that analysis are combined with future projections (by given target dates) of the driving variables, expressed probabilistically. This enables estimates to be made of the likelihood of exceeding certain pre-defined impact thresholds.
6. **Uncertainty analysis** comprises two strands of analysis. First, an inter-comparison of model projections at a given scale (i.e. the scale of a case study, or a pre-determined spatial unit within Europe), where different models are estimating the same outputs. The comparisons can provide clues about structural uncertainties that can feed into the other strands of analysis. Second, formal uncertainty analysis will be undertaken using the multiple scenario runs undertaken in (4) as well as elements of the sensitivity analysis.

For each action, there are associated protocols, which comprise suggestions and guidance on how to undertake an analysis. Protocols may involve describing model features, reviewing some aspects of model results or detailing steps for undertaking new model runs. Some of these are presented in Annexes; others will be prepared later in the project. The protocols are being applied in the context of case studies at different geographical scales in close collaboration with, and guided by, sectoral and regional stakeholders.

1. Introduction

This deliverable describes the overall modelling methodology for the IMPRESSIONS study. It comprises a multi-scale, integrated approach to assessment, focusing on case studies at global, European, national and sub-national scales. The integrated assessment approach was based on the following guiding principles:

- Focusing on adaptation (based on limits to adaptation);
- Integrating across scales and across sectors;
- Supporting model integration through the development of data dictionaries to harmonise model inputs/outputs;
- Using the data dictionaries to establish information flows starting from needs (especially across scales);
- Accommodating scenarios as a starting point (across temporal/spatial scales and sectors);
- Defining what is needed from scenarios (both qualitative/quantitative);
- Dealing with time dependencies;
- Accommodating extreme events and transformative solutions;
- Integrating Shared Policy Assumptions (SPAs);
- Combining mitigation and adaptation trade-offs;
- Communicating outputs to stakeholders; and
- Facilitating synthesis (in WP5).

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

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

The research is ongoing, and while the general methodological framework presented here has already been agreed, and the necessary protocols identified in outline, the implementation of the protocols represents work in progress. Some protocols have been developed in detail and are already underway; others are still being developed and the work is scheduled for a later phase of the project. As such, this report offers an early snapshot of the modelling activity in IMPRESSIONS.

1.1. Description of work

The description of work (DoW) lists three main tasks relating to this deliverable:

- Task 3.1: Development of a multi-scale, integrated assessment approach. This should be a modelling framework that facilitates assessment of sectoral and cross-sectoral impacts of climate change at different scales; appraisal of the effectiveness and limitations of adaptation for reducing risks and exploiting opportunities; evaluation of different sources of uncertainty in estimates of future impacts; comparison of assessments conducted with different models at different scales; and evaluation of risks of exceeding critical impacts or tipping points (defined jointly with stakeholders).

- Task 3.2: Development of guidance and protocols to facilitate implementation of the multi-scale, integrated assessment approach. The protocols should guide modellers in the consistent implementation of the integrated assessment approach across global, European and regional/local scales. They should cover model inputs and outputs, model testing through sensitivity, uncertainty and risk analysis, and the selection, application and analysis of scenarios. They should also provide consistent analytical procedures that can be applied selectively in the different case studies.
- Task 3.3: Representation of the adaptation process in the climate change impacts, adaptation and vulnerability models adopted in the project. This should screen the models used in IMPRESSIONS to establish how they treat adaptation and to diagnose their utility in assessing adaptation options under a wide range of future conditions. It should also review the literature for information on adaptation responses relevant for the IMPRESSIONS case studies. This information will be used to identify causes (triggers), implementation (time lags and uptake), and consequences (efficiency) for the adaptation process.

1.2. Links to other work packages

The integrated modelling approach is founded on close linkages with and between other parts of the IMPRESSIONS project. Primarily this involves a relationship with the project scenario development (WP2) since the scenarios are key inputs to the modelling approach. There are also links to WP4/5 in terms of exploring future visions, and in defining pathways of adaptive actions including transformative solutions. The approach will also provide background framing and primary guidelines for development of the five case studies undertaken in other parts of WP3.

2. Conceptual framework

The purpose of the conceptual framework is to establish a structure within which the model applications are undertaken. It facilitates consistency of modelling across the various case studies, and allows a comparison and synthesis of the model results for commonly defined components of the systems being studied. The conceptual framework is based on an adaptation of the DPSIR (Drivers-Pressures-States-Impacts-Responses) framework (EEA 2002; Rounsevell et al 2010), and is shown in Figure 2.1.

The conceptual framework has a number of advances from previous incarnations of the DPSIR, notably it distinguishes between external and internal drivers, it identifies both negative and positive impacts and by association responses, through both solutions and opportunities, and it is explicit about the role of time including various feedback mechanisms. Hence, the framework has evolved from being static and sequential to dynamic and recursive, thus better allowing the assessment of feedbacks and non-linearities in complex systems.

External (exogenous) Drivers represent the underlying causes of environmental change that are outside the boundaries of the socio-ecological system under consideration. External drivers are embedded within the broader Earth System. External Drivers lead to changes in the Internal (endogenous) Drivers that are a component part of the socio-ecological system. The Internal Drivers change the State of the socio-ecological system, including variables that represent both the biophysical and human system properties. State variables include capitals (social, human, financial, infrastructure, natural) and thresholds that determine when a State becomes an Impact. State thresholds can be physical, mandated (policy defined) or value-based. Impacts can be negative (harmful) or positive (beneficial) with un-avoided Impacts leading to Vulnerability. Impacts trigger Responses that can be based on solutions to negative Impacts or the exploitation of opportunities with positive Impacts. Response triggers can be based on either an actual Impact, or one that is anticipated to occur in advance. Responses act in one of two ways: (i) by increasing capacity (of capitals) or changing thresholds within the States, and (ii) by reducing the magnitude of the threat by acting on the Internal Drivers. A third type of Response is theoretically possible through climate mitigation acting on the External Drivers of climate change, but in practice the magnitude of these effects is likely to be trivial.

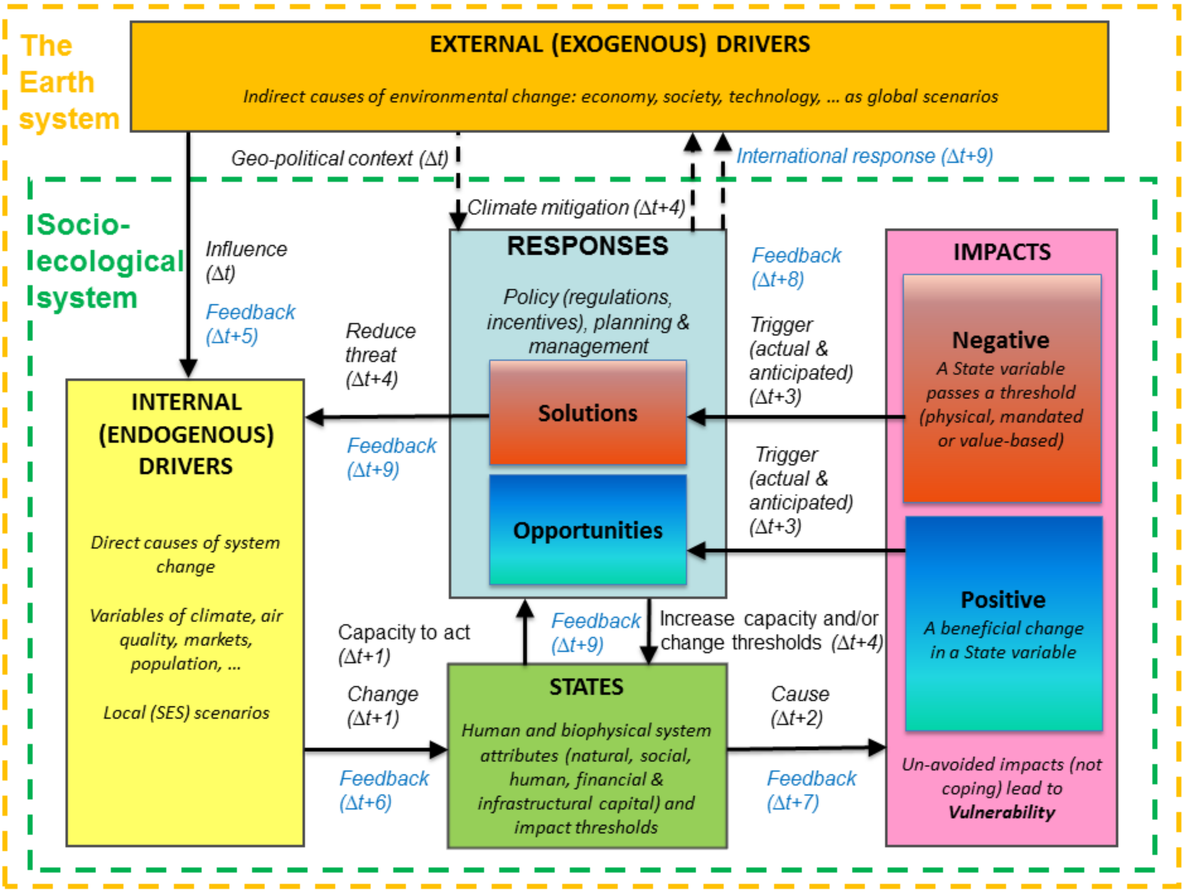

Figure 2.1: The IMPRESSIONS conceptual framework.

The conceptual framework represents a set of stages and actions in the assessment of environmental change on a socio-ecological system of study. It contains feedbacks, e.g. through the responses, and can be iterated through several time-dependent steps. Figure 2.1 also represents the passage of time through the framework, with each time step being dependent on the preceding step. In this way the framework is able to deal with the difficulties inherent in representing complex systems. It is also equally able to represent incremental change as well as transformative solutions.

A worked example of the conceptual framework follows describing a flood event and the response to this event. A change in the global climate (External Driver) leads to new patterns and intensity of rainfall within a region (Internal Drivers) causing changing levels of river water heights (State). When the river level surpasses the flood defences (the defence heights define a physical threshold) then a flood event occurs causing damage to property and livelihoods (negative Impact). The flood event triggers a response in one of two generic ways: (i) increasing capacity or changing the thresholds to act on the State variables, or (ii) reducing the threat by acting on the Internal Drivers. Increasing the heights of flood defences is one way of adapting by changing the Impact thresholds. Improving the capacity to deal with future flood events might also involve changing the fabric and structure of buildings, e.g. using ground levels for car parking only. Reducing the threat could not tackle changing rainfall patterns directly, but it could reduce the magnitude of the threat by either preventing further building in the flood plain, or even relocating households out of the flood prone area. Following these Responses, when the next flood event occurs the socio-ecological system is better able to deal with the consequences, or to avoid them altogether. If the socio-ecological system does not respond adequately to the threat of future flooding then it remains vulnerable, i.e. it is unable to avoid the impacts. Conversely, changing rainfall patterns and intensity might reduce the threat of flooding, which would have a positive Impact. In this case, responses might seek to take advantage of the new opportunities arising from this positive Impact, for example, by reducing the need for expensive flood defence infrastructure.

3. Cataloguing of models

3.1. Questionnaire to modellers

A questionnaire was distributed among IMPRESSIONS partners that plan to apply climate change impacts, adaptation and vulnerability (CCIAV) models. The intention was to collect information about available models and their possibilities for application and refinement in the various WPs of the project. Responses were collected during spring 2014.

CCIAV models in IMPRESSIONS will be used to:

1. Assess sectoral and cross-sectoral impacts of climate change and socio-economic change at different scales;
2. Construct impact response surfaces for examining model behaviour under a range of future conditions to evaluate risks of exceeding critical impacts or tipping points;
3. Investigate the effects of spatial scale on model outcomes through selected inter-comparison studies;
4. Investigate the use of model outputs at higher scale levels as boundary conditions for models operating at lower scale levels;
5. Appraise the effectiveness and limitations of adaptation for reducing risks and exploiting opportunities;
6. Evaluate different sources of uncertainty in estimates of future impacts;
7. Examine the impacts and vulnerabilities for a set of mitigation plus adaptation pathways derived in WP4.

More than 20 CCIAV models are currently planned to be used in the IMPRESSIONS case studies with a broad coverage across sectors (Table 3.1). While the majority of models are well-established, refinements are planned for 10 of the models (from 17 answers), mainly to improve the representation of adaptation, and three new models are being developed in the project (cf. Table 3.1). A wide variety of model types is being used, with most defined as process-based biophysical models (Figure 3.1).

The majority of the models (15) operate on a regular grid (mainly 10’ or 0.5° spatial resolution), the spatial unit for five models is country or NUTS2 regions and three models simulate at the catchment level. Four models reported using period-averages for their input data, whereas most others use year-by-year information.

The model code of five of the impact models was reported as being open source, while eleven models are not. The programming languages that were used to implement the models are all standard modern programming languages (e.g. Java [2 models], C [3], C++ [4], Fortran [2], Silverlight and VB.net). A typical runtime for a model simulation in its corresponding IMPRESSIONS study region varies between seconds (four models), through minutes (four models), to hours (seven models). Ten models can be set up to run simulations in batch mode, while five models cannot.

Table 3.1: Impact models in IMPRESSIONS, their sectorial coverage and intended use in case studies. Three models are being developed during the project (labelled t.b.d. – to be developed) for which no detailed answers were given in the questionnaire. The RUG, SFARMOD, CFFlood, WaterGAP metamodel and SPECIES models are part of the CLIMSAVE IAP, whilst ForClim and the LSHTM health model are being integrated into a new version of the CLIMSAVE IAP for IMPRESSIONS.

Partner	Model	Case study	Sectors
NIES	AIM/Impact[Health]	Global	Human health
NIES	AIM/Impact[Water]	Global	Water resources
NIES	M-GAEZ	Global	Agriculture
NIES	VISIT	Global	Biodiversity, Forestry
WU	GLOBIO	Global	Biodiversity
UNI KASSEL	WaterGAP2	Global, Europe	Water resources
NCAR	iPETS	Global, Europe, other(s)	Agriculture, Energy, Forestry, Urban, Trade, household consumption (spatial population projections)
SSSA	Keynes+Schumpeter / ENGAGE	Global, Europe	Energy, capital- and consumption-good industry
CNRS	Lagom Generic 2.0, LagomRegio 1.0	Europe	Economics
UEDIN	CRAFTY 1.0	Europe	Agriculture, Forestry, Land use
TIAMASG	CLIMSAVE IAP	Europe, Scotland	Integrated containing Urban, Agriculture, Water, Forestry, Biodiversity, Coasts
CRANFIELD U	SFARMOD	Europe, Scotland	Agriculture, Forestry
ETH ZURICH	ForClim v3.2	Europe, Scotland	Forestry
TIAMASG	CFFlood Model	Europe, Scotland	Flooding, Wetlands
UNI KASSEL	WaterGAP metamodel (IAP)	Europe, Scotland	Water resources
UOXF	SPECIES	Europe, Scotland	Biodiversity
UEDIN/UOXF	RUG (Residential Urban Growth)	Europe, Hungary	Urban
LSHTM	Heat-related mortality (t.b.d.)	Europe, Hungary	Human health
PIK	SWIM	Europe (selected river basins), Iberia, Scotland	Agriculture, Energy, Water resources
UOXF/UEDIN	Aporia	Hungary, Scotland	Agriculture, Forestry, Land use
ETH ZURICH	LandClim v1.4	Iberia	Forestry
UOXF	Lyme disease (t.b.d.)	Scotland, Hungary	Human health
UEDIN	Tourism model (t.b.d.)	Scotland	Tourism

The future time horizon for which modellers think their model is applicable extends to future decades in most cases (four until 2030, two until 2050), with 11 models reportedly capable of simulating until the end of the 21st century. Many of the established models have already been used with high-end climate scenarios. Note that a review of past model runs is also being conducted in the project (see section 5.2).

A report listing all responses to the questionnaire is available on the IMPRESSIONS internal website at http://impressions-project.eu/library.php > WP documents > WP3 documents. Note also that some of the details regarding model input and output data were subsequently collated in 24 data dictionaries (see below).

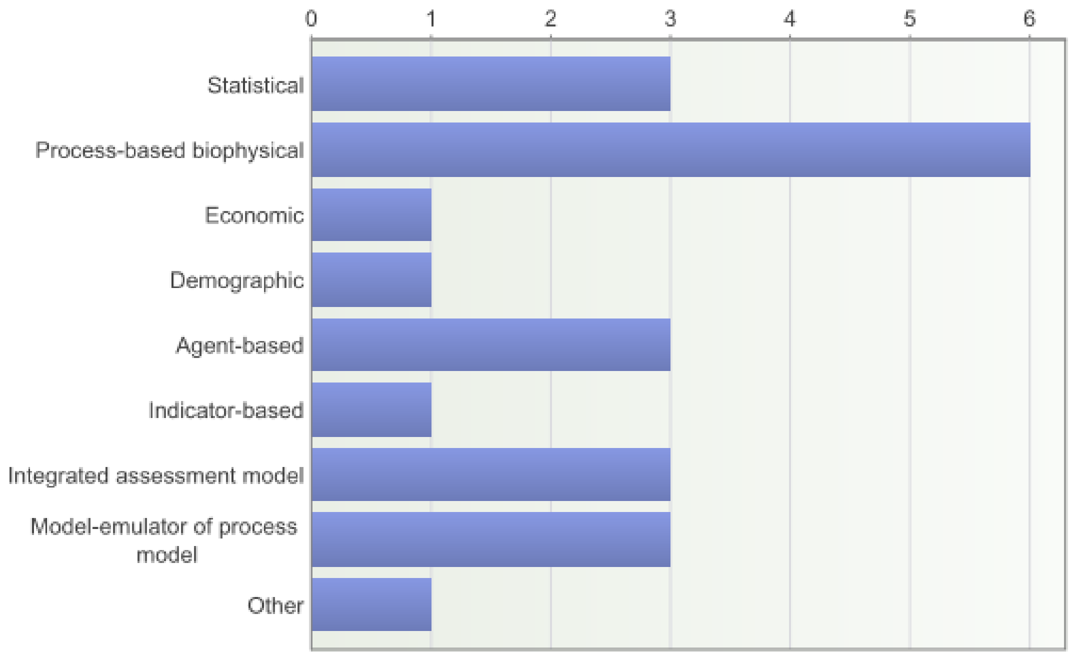

Figure 3.1: Types of impact models used in IMPRESSIONS based on questionnaire responses (n=17).

3.2. Data dictionaries

Data dictionaries describing the input and output variables/parameters of models that are being applied in the project were constructed. Data dictionary is used here to refer to a repository of information about data in a model, e.g. variables, units, scale of application, relationships to other data and format.

Within IMPRESSIONS the data dictionaries serve several purposes:

- Information: for documenting model attributes and the potential utility of model outputs;
- Data transfer: for hard linking models to exchange data (e.g. cross-sectoral interactions);
- Data transfer: for soft linking models to exchange information (e.g. as boundary conditions);
- Model inter-comparison: for evaluating whether output variables from different models are amenable to inter-comparison.

Altogether 24 data dictionaries (one per model) were constructed. Each data dictionary is presented as an Excel file with the first worksheet providing general information on the model (e.g. sector of the model, modelling approach, study regions covered) and contact details. The second worksheet gives information on the input variables/parameters of the model and the third on the output produced by the model. Collectively this information was used to prepare modelling protocols for running and analysing models in IMPRESSIONS.

The 24 Excel workbooks containing the data dictionaries can be downloaded from the IMPRESSIONS internal website at: http://impressions-project.eu/library.php > WP documents > WP3 documents > Data dictionaries.

4. Multi-scale modelling framework

The IMPRESSIONS case studies are applied at three geographic scales: global, European and regional (sub-national). There are three regional case studies within Europe: Scotland, the Iberian Peninsula and Hungary. Figure 4.1 shows the relationships between the three geographic scale levels. In some cases (indicated in red) there is a flow of data from the higher to lower scale levels, in other words the model outputs at a higher scale level provide boundary conditions for model inputs to a lower scale level. In other cases the relationship between scale levels is based on a comparison of model outputs across scales (indicated in green). So for example, the global models will generate outputs that cover the European continent, which can be compared with the outputs from the pan-European modelling. Figure 4.1 also identifies which modelled variables are relevant as boundary conditions and which are relevant to a model inter-comparison, as well as the names of the models concerned. Note, in addition, that a further case study is being conducted on the implications for Europe of future climate change impacts in the former Soviet central Asian republics. Few models are available for simulating such "indirect" impacts for Europe, though some insights can be gained from the global models (dotted purple arrow in Figure 4.1).

The identification of model linkages and boundary conditions was undertaken through a process of modeller enquiry (using a questionnaire – section 3.1) and the development of model data dictionaries (section 3.2). This approach is described in the following section.

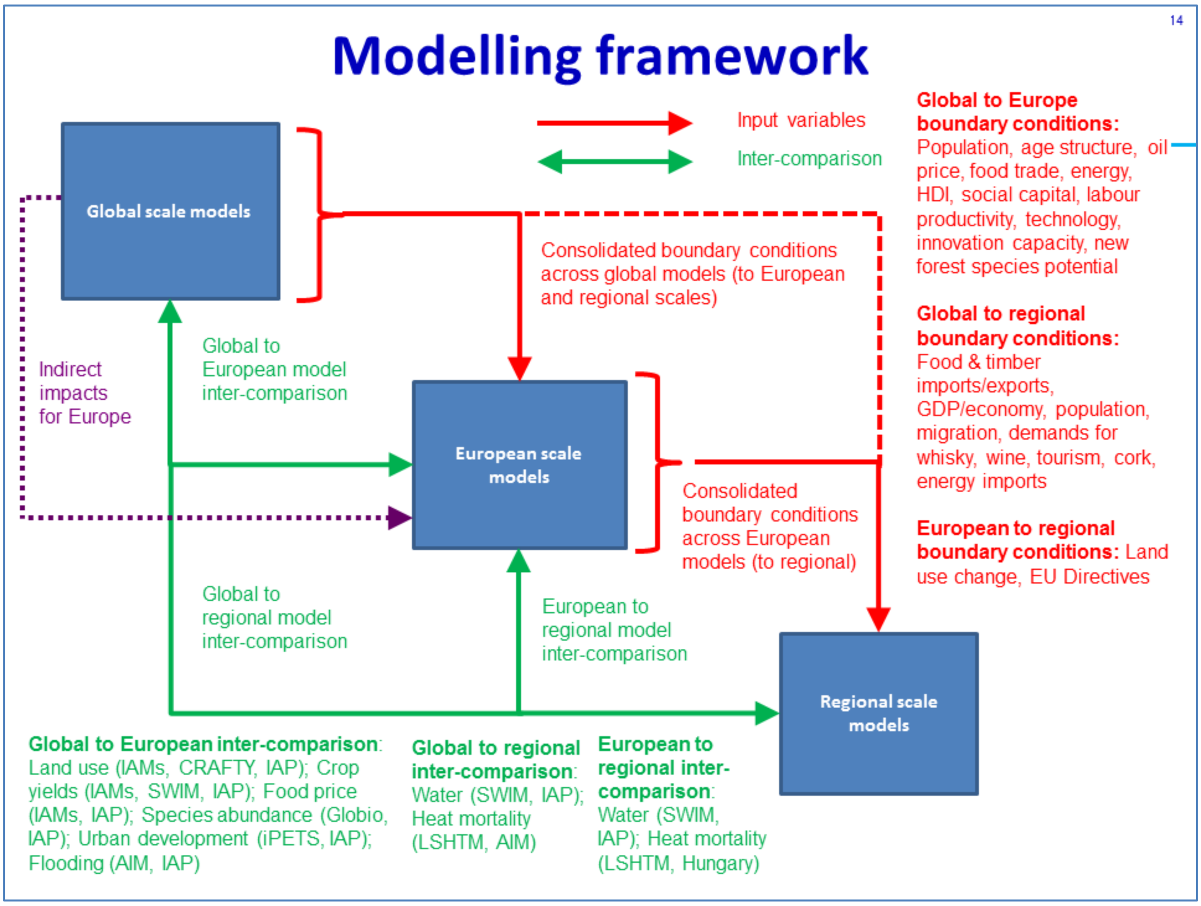

Figure 4.1: The three geographic levels of modelling (global, European and regional) showing boundary conditions (red) and preliminary list of variables for cross-scale model inter-comparison (green).

4.1. The modelling framework demonstrating model linkages

The modellers' questionnaire and the development of the data dictionaries enabled the linkages between each of the models used within the five case study areas to be identified. These linkages and further details about the exchange of specific variables between named models are illustrated in Figure 4.2. Whilst all of the case studies are operating within a common conceptual framework, there are very different modelling tools (reflecting different modelling paradigms) across the three geographic scale levels. At the regional scale, the models are similar, but there are clear differences in the ways in which the models will be applied. This generally reflects the different topics and objectives of each case study. Table 4.1 indicates the boundary conditions across the geographic scale levels, providing details about which model will provide data for another model and scale level.

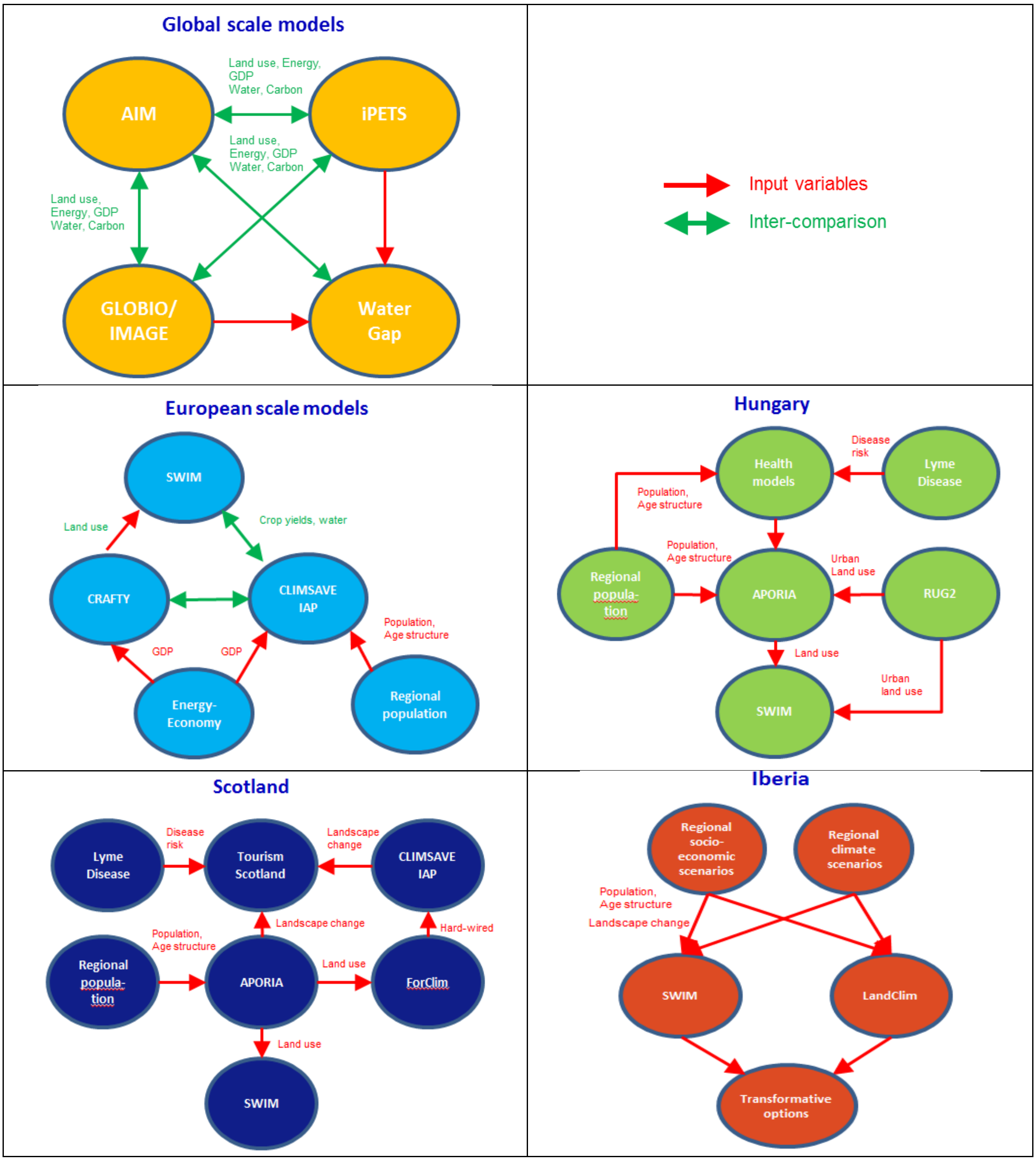

Figure 4.2: Linkages between models for each case study, including the exchange of variables.

Table 4.1: Exogenous input variables (boundary conditions) for IMPRESSIONS models and their potential sources based on information in the data dictionaries. Input source: O – observed dataset, R - other regional case study model, G – global model, SSP – SSP database at IIASA, ? – to be specified. A more detailed version of this table is available at http://impressions-project.eu/library.php > WP documents > WP3 documents > Data dictionaries.

Model	Variable	Input source	Input source details
CFFlood meta	Sea-level rise	?	HELIX, RISES-AM or literature
CFFlood meta	Population (baseline)	O	NUTS3 dataset
CFFlood meta	Population change	SSP	Socio-economic scenario
CFFlood meta	GDP (baseline)	O	NUTS3 dataset
CFFlood meta	GDP change	SSP	Socio-economic scenario
CRAFTY 1.0	Productivity of land for agricultural crops, livestock, forestry	R	CLIMSAVE IAP
CRAFTY 1.0	Financial support for land uses	?	
CRAFTY 1.0	Naturalness' or natural amenity	R	CLIMSAVE IAP
CRAFTY 1.0	Current land use	O/R	CORINE or SFARMOD/IAP
CRAFTY 1.0	Demand for land-use goods/services	G	IMAGE agric., food and forestry demand
CRAFTY 1.0	Productive abilities of agent	?	Derived from SSPs for Europe
ForClim v3.3	Available nitrogen	?	Database, modelled?
Heat-related mortality	Age-specific mortality rates	SSP	WHO data or SSP
H. mortality	Age-specific population	SSP	SSP and RUG2
H. mortality	Urban indicator	R	RUG2
H. mortality	Socio-economic indicator	?	tbc (income, HDI, etc)
Lyme disease	Maps of vegetated areas	O/R	CORINE or CLIMSAVE IAP
Lyme disease	Population distribution of deer	R	SPECIES
Lyme disease	Distribution of residents	R	RUG2
Lyme disease	Indicators of time use and participation in woodland activities	G	IMAGE indicators for forest management
RUG (Residential Urban Growth)	GDP change	SSP	
RUG	Population change	SSP	SSP (downscaled)
SFARMOD	Change in crop prices	G	IMAGE
SFARMOD	Change in real costs	?	Derived from SSPs for Europe
SFARMOD	Technological change	?	Derived from SSPs for Europe
SFARMOD	Change in labour cost	?	Derived from SSPs for Europe
SFARMOD	Yield change (breeding + agronomy)	?	Derived from SSPs for Europe
SFARMOD	Policy pressure to reduce ruminants	?	Derived from SSPs for Europe
SFARMOD	Policy press. to reduce white meat	?	Derived from SSPs for Europe
SFARMOD	Policy press. to increase bioenergy crop production	G	IMAGE indicator for Primary energy: Biomass
SFARMOD	Reduction in crop yield potential due to reduced fertiliser inputs	?	Derived from SSPs for Europe
SFARMOD	Cost of irrigation water	?	Derived from SSPs for Europe
SFARMOD	Change in irrigation efficiency	?	Derived from SSPs for Europe
SFARMOD	Increase EU agrarian imports	?	Derived from SSPs for Europe
SFARMOD	% land removed from production	?	Derived from SSPs for Europe
SWIM	Point sources of pollution		Regional datasets
SWIM	Reservoirs characteristics	?	Regional or global database

4.2. Adaptation responses

The approaches used in CCIAV models to treat adaptation were screened based on the responses to the questionnaire. Their utility in assessing adaptation options under a wide range of future conditions was appraised so that possible improvements in the parameterisation of the adaptation process within the WP3 CCIAV models could be proposed. Recent reviews (Patt et al., 2010; Fisher-Vanden et al., (2011); Dickinson, 2007) have highlighted the general weakness of integrated assessment and sectoral models in representing adaptation. Dickinson (2007) sub-divided models into 'impact centred models' and 'adaptation centred models' according to the general approach to representing adaptation (Table 4.2). However, although Dickinson (2007) classified each of the 35 models in their review by descriptors (agent-based; behavioural; cost-benefit analysis; integrated assessment model; optimisation; qualitative; quantitative and simulation), few insights were gained other than "sectoral" gaps (including health, extreme weather events, globalisation, abrupt climate change and biodiversity) and the need for human behaviour to be an essential component in an adaptation model.

Table 4.2: Summary of the main differences between 'impact-centred' and 'adaptation-centred' models (from Dickinson, 2007).

Impact-centred models (ICMs)		Adaptation-centred models (ACMs)	
Characteristics	**Comments**	**Characteristics**	**Comments**
Models measure impacts of climate change; modelling impacts parameterising adaptation	Impacts net of adaptation, not gross impacts Normative	Allows for the variation of adaptation options or different levels of adaptation	Allows for how much can be accomplished through adaptation; given the impacts, how much adaptation could or would occur
Adaptation is incorporated in an unchanging equation assumed to take adaptation into account	This is not 'modelling adaptation'	Adaptation can be manipulated, assessed and evaluated	Potential to demonstrate the strengths/weaknesses of adapting to climate change
Adaptation cannot be varied in the model	Parameter set or assumed at static level	ACMs demonstrate the ability of adaptation to reduce climate change impacts	ACMs are much more satisfactory than ICMs and they represent a more promising direction for future development
The amount of adaptation (or net of achievement) is assumed and is not verified, nor does it have an empirical basis	Thus, the output is based on the inclusion or exclusion of adaptation, but adaptation itself is not being modelled		

Adaptation can involve both building adaptive capacity (thereby increasing the ability of individuals, groups or organisations to adapt to changes) and implementing adaptation decisions, i.e. transforming that capacity into action. However, within this broad scope, adaptation responses can be differentiated along a number of dimensions which include:

- **Intent or purpose** – differentiating between responses that occur autonomously (autonomous adaptation) or are planned (planned adaptation);
- **Timescale** – differentiating between (short-term) tactical or reactive responses and (longer-term) strategic or anticipatory changes;

- **Spatial scale** – differentiating between adaptations that occur at national, regional or local scales;
- **Beneficiaries and providers** – differentiating between adaptations taken by public or private actors;
- **Type of action** – differentiating between physical (engineering; technological), investment, market, social and institutional adaptation measures;
- **Sector** – differentiating between narrowly focused sectoral adaptations to a more holistic cross-cutting approach.

Such dimensions of adaptation suggest a number of key factors that characterise adaptation from a real-world perspective:

- *reactive* and *anticipatory* adaptation are approaches differentiated by their timing in relation to the climate stimulus; in addition to this, *short-* and *long-term* approaches relate to the temporal scope of the adaptation strategy;
- *reactive* and *anticipatory* adaptation are also differentiated by whether a trigger or critical threshold has been breached or not;
- the availability of *multiple* specific adaptation options to address an actual or perceived impact requires criteria to *prioritise* options, which in turn requires an understanding of the likely effectiveness of each measure in contributing to achieving a range of objectives or goals;
- *private* and *public* adaptation that draws attention to the role played by societies and institutions in the process;
- the practicability and effectiveness of engineering and technological adaptation measures are bound by the availability of technology and economic resources. Consequently, adaptive capacity constraints originated by the economy, society and technology are identified;
- Moving from *sectoral* adaptation strategies to *cross-sectoral* integration of adaptation planning facilitates the identification of trade-offs and synergies.

Given the above, the IMPRESSIONS modellers were asked within the WP3 CCIAV model questionnaires whether their model(s):

- Explicitly modelled adaptation or whether adaptation was implemented by the user subjectively changing model inputs;
- What elements of the adaptation process (e.g. triggers, timelags, uptake, effectiveness and constraints) are explicitly included in the model?
- Whether adaptive capacity is considered by the model.

The results are summarised in Table 4.3. It is apparent that, although the models are able to simulate a broad range of sectoral adaptation responses (not shown in the Table), most do this through subjective decisions and manual changes made by the modeller. Furthermore, few of the models explicitly include the key characteristics of adaptation.

Given the diversity of model types being used within IMPRESSIONS from global Integrated Assessment Models to institutional Agent-Based Models, it is inappropriate to define one approach to representing adaptation. However, where practicable, IMPRESSIONS modellers will aim to improve the treatment of adaptation by using empirical insights on the causes (triggers), implementation (time lags and uptake), and consequences (efficiency; constraints) gained from case studies within the peer-reviewed and grey literature (including information that can be obtained from studying adaptation in analogue regions or in relation to past events).

Table 4.3: Summary of responses to the IMPRESSIONS CCIAV model questionnaire regarding the treatment of adaptation.

Case study	Model	Sector	Modelling approach	Is adaptation explicitly modelled?	Adaptation elements included within model					How is adaptive capacity treated?
					Trigger	Constraints	Timelags	Uptake	Effectiveness	
Global	AIM/Impact[Health]	Human health	Statistical	No						not treated
Global	AIM/Impact[Water]	Water resources	Emulator of process model	No						not treated
Global	M-GAEZ	Agriculture	Process-based biophysical	Yes (autonomous)						not treated
Global	VISIT	Biodiversity, Forestry	Process-based biophysical	No						not treated
Global	GLOBIO	Biodiversity	Statistical, Indicator-based	No						not treated
Global, Europe	WaterGAP2	Water resources	Process-based biophysical with soc-econ. inputs	Yes (autonomous)						not treated
Global, Europe, other(s)	iPETS	Agriculture, Energy, Forestry, Urban, Trade, household consumption	Integrated assessment model	Yes (autonomous)		✓				not treated
Global, Europe	Keynes+Schumpeter / ENGAGE	Energy, capital- and consumption-good industry	Agent-based	No						not treated
Europe	Lagom Generic 2.0, LagomRegio 1.0	Economics	Agent-based	No						not treated
Europe, Regional	CRAFTY 1.0	Land use Agriculture, Forestry	Agent-based	Yes (autonomous)					✓	indicators at fixed levels
Europe, Regional	CLIMSAVE IAP	Urban, Tourism, Agriculture, Water, Forestry, Biodiversity	Integrated assessment model	Yes	✓	✓ various		✓	✓	Indicators projected into the future

Case study	**Model**	**Sector**	**Modelling approach**	**Is adaptation explicitly modelled?**	**Adaptation elements included within model**					**How is adaptive capacity treated?**
					Trigger	Constraints	Timelags	Uptake	Effectiveness	
Europe	SFARMOD	Agriculture, Forestry	Emulator of process model, Economic, Integrated assessment model	Yes (autonomous)	✓ food	✓ biophysical		✓		not treated
Europe	ForClim v3.3	Forestry	Process-based biophysical	No	✓ climate	✓ biophysical	✓ biophysical			not treated
Europe	CFFlood Model	Biodiversity, Flood	Emulator of process model, Other	No				✓		not treated
Europe, Regional	WaterGAP metamodel (IAP)	Water resources	Emulator of process model	No		✓ capital				not treated
Europe, Regional	SPECIES	Biodiversity	Neural networks	No						not treated
Europe, Regional	RUG (Residential Urban Growth)	Urban	Statistical	No		✓ planning				not treated
Europe (selected river basins)	SWIM	Agriculture, Energy, Water resources	Process-based biophysical	No						not treated
Regional	Aporia	Land use Agriculture, Forestry,	Agent-based	Yes (autonomous)		✓ capital		✓		not treated
Regional	LandClim v1.4	Forestry	Process-based biophysical	No	✓ climate	✓ biophysical	✓ biophysical			not treated

5. Modelling strategy and protocols

5.1. Overview

The modelling strategy comprises a number of actions that all modelling groups need to consider in IMPRESSIONS. These are depicted in Figure 5.1 as blue boxes. Actions are specific pieces of analysis relating to a model. They have been identified to address some of the common objectives of the IMPRESSIONS project and there is a chronological order in which these actions would logically be taken (arrows). For each action, there are associated protocols, which comprise suggestions and guidance on how to undertake an analysis (beige boxes). Protocols may involve describing model features (already outlined in Section 4, above), reviewing some aspects of model results or detailing steps for undertaking new model runs. The actions involved may also be contingent on the answer to a question requiring a decision. Some actions may need to be repeated, as new results are obtained and new questions emerge, requiring iteration (dashed arrows). Details of the different actions and associated protocols are described in the following sub-sections.

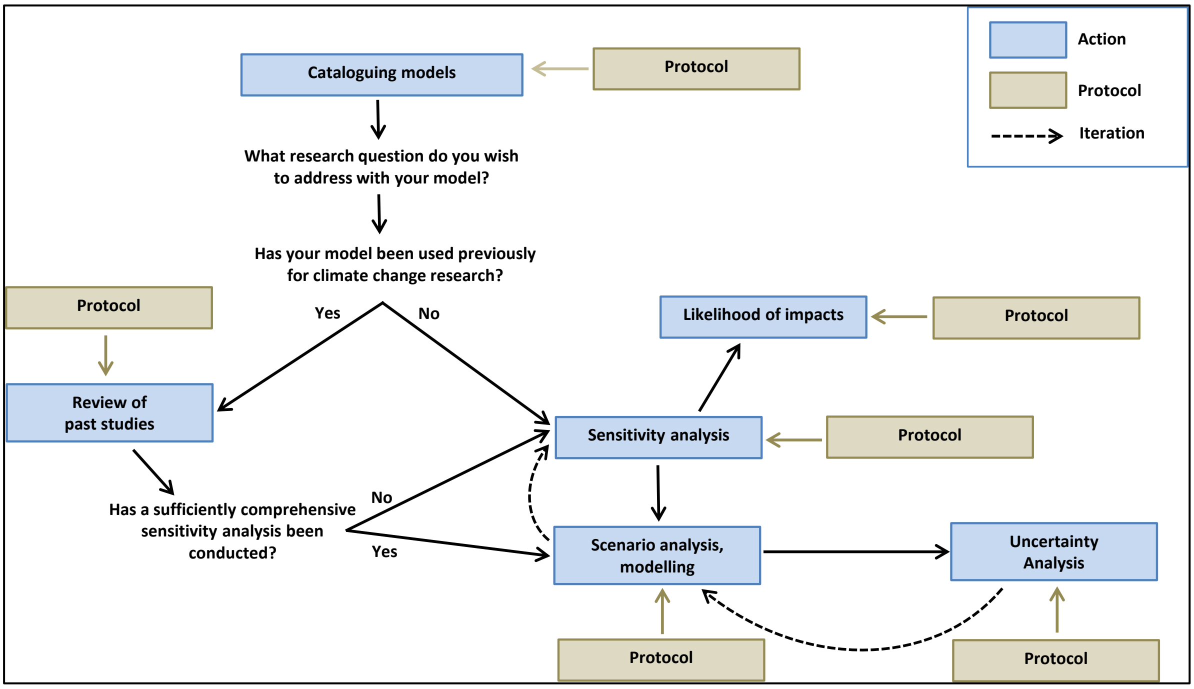

Figure 5.1: Modelling strategy for IMPRESSIONS.

As a quick guide, six actions are depicted in **Error! Reference source not found.**.1:

(i) Cataloguing models involves describing model characteristics (through the questionnaire – section 3.1), inputs and outputs (via the data dictionaries – section 3.2) and also refers here to the modelling framework, including model linkages (section 4.1) and the treatment by models of adaptation (section 4.2).

(ii) If a model has already been developed it should be reviewed. Review of past studies, is a scan of past work with the model that might offer insights about model sensitivity to climate change, especially at the high-end of climate projections, as well as information about its fitness for the purpose of application under high-end scenarios in IMPRESSIONS.

(iii) Sensitivity analysis refers to simulations, with simplified model assumptions, that explore responses of important model outputs to a range of key input variables. For many models, these will be climate variables (predominantly temperature and precipitation), but other climate or socio-economic variables can also be selected. This exercise serves three main purposes. First, it offers a method of testing model sensitivity to a plausible range of future conditions comparable to those found in the scenario analysis (see (iv) below). For new models, this offers an initial test of model suitability for application. For existing models, it may extend the range of conditions being tested. Second, the procedure offers an opportunity to compare model outputs for the same range of driving variables using impact response surfaces. Third, this initial sensitivity analysis is a pre-requisite for applying models with probabilistic projections in evaluating likelihood of impacts (see (v) below). So, even if the fitness for purpose of a model across a range of future conditions can be demonstrated by past analysis (see (ii) above), sensitivity analysis is still recommended for all models to serve the second purpose (inter-comparison) and perhaps also the third (impact likelihoods).

(iv) Scenario analysis is the core activity involving impact model projections through to 2100. It involves the application of climate and socio-economic scenarios defined in WP2 based on the RCP/SSP global scenario framework, and is also guided by the adaptation and mitigation pathways developed in WP4. This analysis is both informed by (e.g. through model behaviour under high-end forcing) and feeds back into (e.g. by defining key driving variables) the sensitivity analysis.

(v) Likelihood of impacts involves an advanced sensitivity analysis for key driving variables with more realistic model assumptions than in (iii) above. The impact response surfaces generated by that analysis are combined with future projections (by given target dates) of the driving variables, expressed probabilistically. This enables estimates to be made of the likelihood of exceeding certain pre-defined impact thresholds. This action is contingent on undertaking the initial sensitivity analysis.

(vi) Uncertainty analysis comprises two strands of analysis. First, an inter-comparison of model projections at a given scale (i.e. the scale of a case study, or a pre-determined spatial unit within Europe), where different models are estimating the same outputs. Some options for such comparisons are discussed in section 3. The comparisons can provide clues about structural uncertainties that can feed into the other strands of analysis. Second, formal uncertainty analysis will be undertaken using the multiple scenario runs undertaken in (iv) as well as elements of the sensitivity analysis. Insights from the uncertainty analysis may also feed back to the scenarios analysis.

5.2. Review of past studies

Findings from past studies with the models applied in IMPRESSIONS are being summarised in a short report for each model. The aim of the review is to give an overview of model behaviour under high-end scenarios (HES) according to findings from past studies and model runs already conducted. Modellers have been asked to specify past studies with their model and summarise findings of these in a short Word document. These documents will be compiled into a summary report. The full protocol for conducting the review of past studies is given in Annex A: Review of past studies. This offers a template of the issues that should be considered in the review, for which modelling groups should provide content on the basis of past studies with their models. The protocol was sent out to modelling groups in January 2015 for return and compilation during the autumn of 2015.

5.3. Sensitivity analysis

The sensitivity analysis in IMPRESSIONS is conducted by applying the impact response surface approach (IRS). An IRS is a graphical device for plotting the modelled behaviour of an impact variable in response to changes in two key explanatory variables that span the x- and y-axes of the plot. A key benefit of the IRS method is that it is a systematic way of analysing the sensitivities of an impact model to changes in the variables being tested and provides impact estimates across a wide range of conditions.

The sensitivity of an impact variable (Z) to changes in two key drivers (X and Y) is tested by modifying values of baseline data of X and Y (for a reference date or period) over systematic increments so that the changes span the range of changes projected for the future period of interest. All other aspects are chosen to represent baseline conditions and are kept fixed throughout the perturbations to X and Y. By keeping all other variables fixed while changing only two key drivers (X and Y), the sensitivities can be analysed similarly everywhere without introducing additional dimensions to the analysis. The results of the analysis can be plotted as IRSs that visualise the sensitivity of the impact variable (Z) to changes in the two driving variables (X and Y). Sensitivities across different sectors and regions can be compared by plotting the results side by side (Figure 5.2).

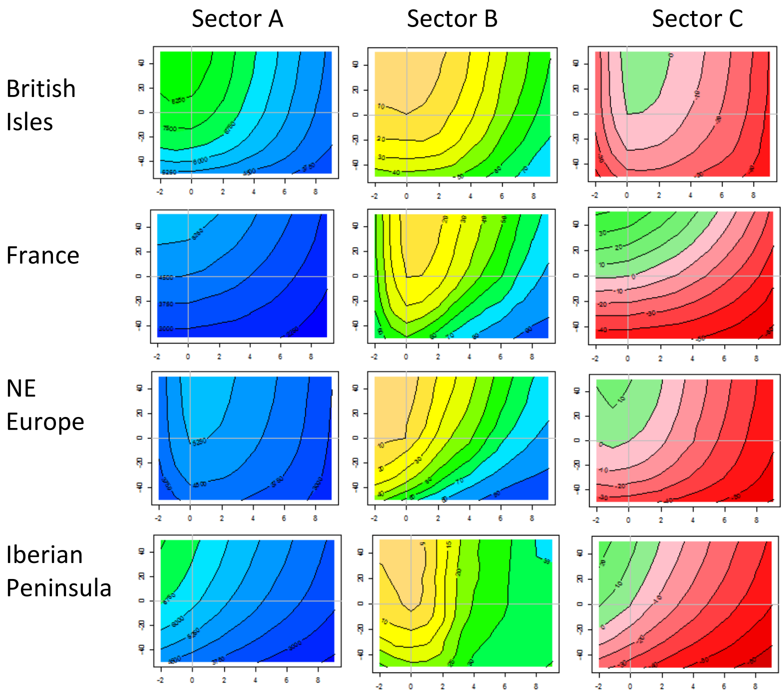

Figure 5.2: Dummy example presenting impact response surfaces for modelled impacts in different sectors under changes in two driving variables over sub-regions of Europe.

The protocol on conducting the sensitivity analysis is provided in Annex B: Sensitivity analysis using the IRS method.

5.4. Likelihood of impacts

The IRS approach used in conducting the sensitivity analysis of the models can be extended further to estimate likelihoods of certain specified impacts occurring by combining IRSs with probabilistic projections for the same two variables. Impacts can then be assessed within a quantified risk framework. The method is typically applied in the context of changes in climatic explanatory variables. The approach was developed in the EU FP6 ENSEMBLES project, with case studies from various sectors. The principles of the approach are described in Fronzek et al. (2010) and two case studies with crop models were presented by Børgesen and Olesen (2011) and Ferrise et al. (2011).

The method applied for testing the sensitivity of an impact variable to changes in two drivers is used as a starting point for extending the analysis to estimate the likelihood of future impacts. This is a two-step process that involves:

- developing the method to improve realism in model simulations, and then performing simulations for different combinations of scenarios and adaptation options;
- constructing IRSs from the simulation results and combining those with probabilistic projections of changes to the driving variables to estimate impact likelihoods with respect to defined critical impact thresholds.

Similarly to the sensitivity analysis, results for different sectors and regions can be compared by plotting the results side by side (Figure 5.3). The results of different sectors and regions may include different elements and region-specific adaptations as for each sector the primary aim is to make the results of the IRS as realistic as possible.

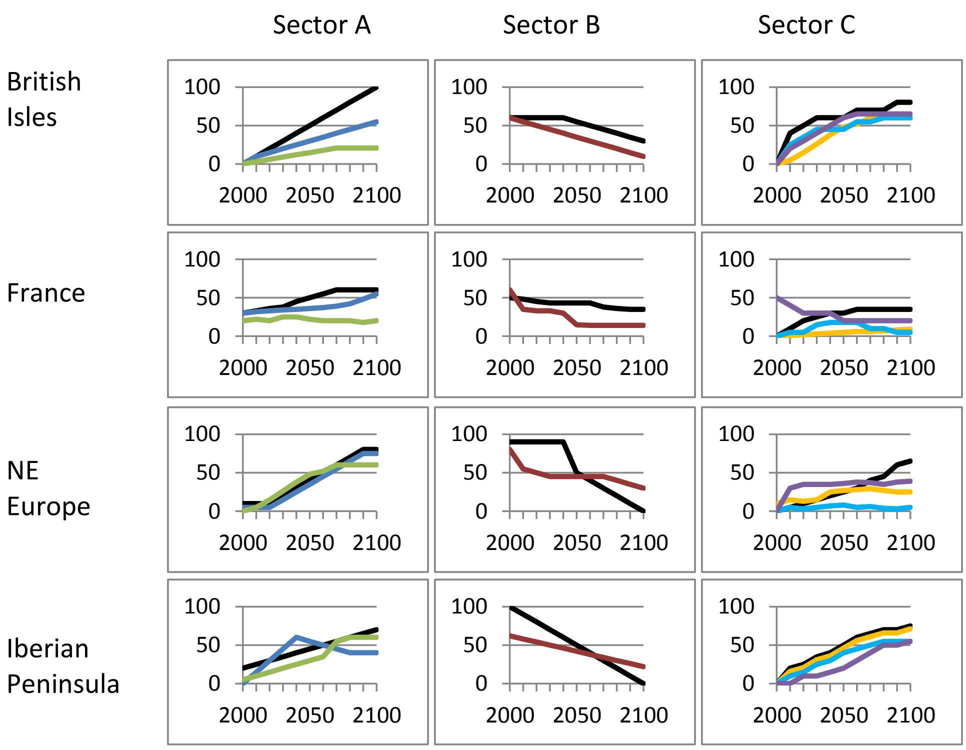

Figure 5.3: Dummy example presenting the evolution through time of the likelihood of exceeding/falling short of a chosen impact threshold for different sectors and regions under one scenario and under different adaptations (coloured lines).

In the second modellers' meeting in Pisa (September/October 2014) it was decided that a working group would be organised to discuss this more complex approach to using the IRS method and alternative approaches. The suggestion is to organise the working group from among the participants of the sensitivity analysis. Based on the decision made by the group, a protocol will be developed.

5.5. Scenario analysis

Climate and socio-economic scenarios are being developed in IMPRESSIONS WP2 using the global framework of RCPs/SSPs. Their application as input for CCIAV models in the case studies is specified in a dedicated protocol that has been developed in parallel with the scenarios themselves. The protocol is described in Annex C, and gives recommendations for the application of the scenarios in two phases.

5.5.1. Phase 1: Initial scenario analysis supporting the second case study stakeholder workshops

The central objective of Phase 1 of the Scenario Analysis is to undertake an initial impact, adaptation and vulnerability (IAV) assessment using relevant model simulations for each case study that can inform discussions at the second set of stakeholder workshops (WS2) scheduled during 2016 (see Table 6.1). The specific aims of these simulations are:

1. To establish present-day impacts and vulnerabilities for key output variables in the case study region that are representative of the current baseline period (up to 2010), using baseline climate and socio-economic input data and other relevant baseline assumptions.
2. To estimate future impacts and vulnerabilities under high-end and other scenarios for key output variables in the case study region out to 2100, assuming no explicit adaptation, by perturbing the baseline input data according to each of five feasible combinations of RCP-based climate projections (core projections) and SSP-based socio-economic projections (Table 5.1).
3. Where feasible, to simulate the effectiveness of explicit adaptation measures in ameliorating impacts and vulnerabilities in the case study region during the period to 2100.
4. If possible, to improve the representation of uncertainties in projections by undertaking model simulations for an extended scenario ensemble.
5. To deliver model outputs in a consistent format for interpretation, possible comparison and eventual dissemination in the case study workshops.

Table 5.1: Five combinations of socio-economic (SSP-based) and climate (RCP-based) projections to 2100, in suggested rank order, for application in model scenario analysis. Short descriptors of global SSPs are from O'Neill et al. (2015). Climate projections are as shown in Annex C, Figure C1 which are specified in terms of specific GCM/RCM combinations in Deliverable 2.1.

Priority	Socio-economic projection		Climate projection	
	SSP	Short descriptor	RCP	Core GCM/RCMs
1	SSP3	Regional rivalry	RCP8.5	1, 2, 3, 7
2	SSP5	Fossil-fuelled development	RCP8.5	1, 2, 3, 7
3	SSP1	Sustainability	RCP4.5	4, 5, 6
4	SSP3	Regional rivalry	RCP4.5	4, 5, 6
5	SSP4	Inequality	RCP4.5	4, 5, 6

Modelling procedures addressing each of these aims are still being finalised, with draft proposals outlined in more detail in Annex C.

5.5.2. Phase 2: Integrated scenario analysis supporting the third case study stakeholder workshops

The main objective of Phase 2 of the Scenario Analysis is to design and then undertake a revised set of IAV model simulations (iterations) based on comments and suggestions received and information requested during the second stakeholder workshops (WS2). The new simulations will also address, more explicitly, some of the adaptive and transformative pathways towards a sustainable future discussed by stakeholders and formalised in normative pathways developed in WP4. Phase 2 simulations will provide integrated results and analysis for each case study as input to the third set of stakeholder workshops (WS3) during 2017. Modelling procedures for Phase 2 will be developed in 2016.

5.6. Uncertainty analysis

Protocols for the uncertainty analysis are still under development as this work will build on the sensitivity and scenario analysis. This work is scheduled for the latter half of the project, and detailed protocols will be developed at that time. Uncertainty analysis comprises two strands: model inter-comparison and systematic uncertainty analysis.

5.6.1. Model inter-comparison

An inter-comparison of model projections will be undertaken at a given scale (i.e. the scale of a case study, or a pre-determined spatial unit within Europe), where different models are estimating the same outputs. Some options for output variables that could be compared are shown in Figure 4.1. The comparisons can provide insight into model structural uncertainties and differences that can support other strands of analysis. An inter-comparison will be undertaken within each geographic scale level where relevant (e.g. global and European scales) for key model output variables, e.g. land use areas. This will include a comparison of the land use areas for the IAM models at the global scale, and a comparison of the land use outputs for the rIAM[1] and CRAFTY models at the European scale. An analysis will also be made of model results across scale levels, e.g. the European land use areas generated by the global IAMs will be compared with the areas produced by the European models. This analysis will explore the effects of model types, scenario, spatial resolution and other variables on the differences in the model outputs. The analysis will require each of the modelling groups to provide scenario-based model output within an agreed format.

5.6.2. Other forms of uncertainty analysis

Formal uncertainty analysis will be undertaken using the multiple scenario runs undertaken in the scenario analysis (Section 5.5) as well as elements of the sensitivity analysis (Section 5.3). This will be supplemented by traditional numerical validation approaches combined with modeller interviews and network analysis to quantify error propagation through the linking of different models following the approach used for the CLIMSAVE IAP (Dunford et al., 2014).

In addition to advance understanding of scenario uncertainties, a probabilistic approach will be implemented where feasible depending on model runtimes and computing capacity. This involves creating probability density functions (PDFs) of model input parameters that are conditional on the scenario assumptions. A Monte-Carlo based sampling across all of the input PDFs is then undertaken involving multiple (several thousand) simulation runs. The outputs from these simulations can then be summarised as output PDFs for key variables that are conditional on the scenarios. Comparing PDFs of model outcomes across all of the scenarios will provide insights into the robustness of the sectoral and cross-sectoral responses in time and space. Robust responses converge towards a single narrow PDF and help to identify the low probability, high impact outcomes at the tails of the distribution. Other responses may show divergent behaviour resulting in broad or multi-peaked distributions. This approach will also identify the role of autonomous adaptation in limiting the deleterious outcomes at the extremes of the distributions, thereby identifying those spatial units

[1] rIAM is the Regional Integrated Assessment Model, an extended and renamed version of the CLIMSAVE IAP.

that will benefit from planned adaptation. An example of a probabilistic uncertainty analysis that has been undertaken for the CLIMSAVE IAP is shown in Figure 5.4 (Brown et al., 2015).

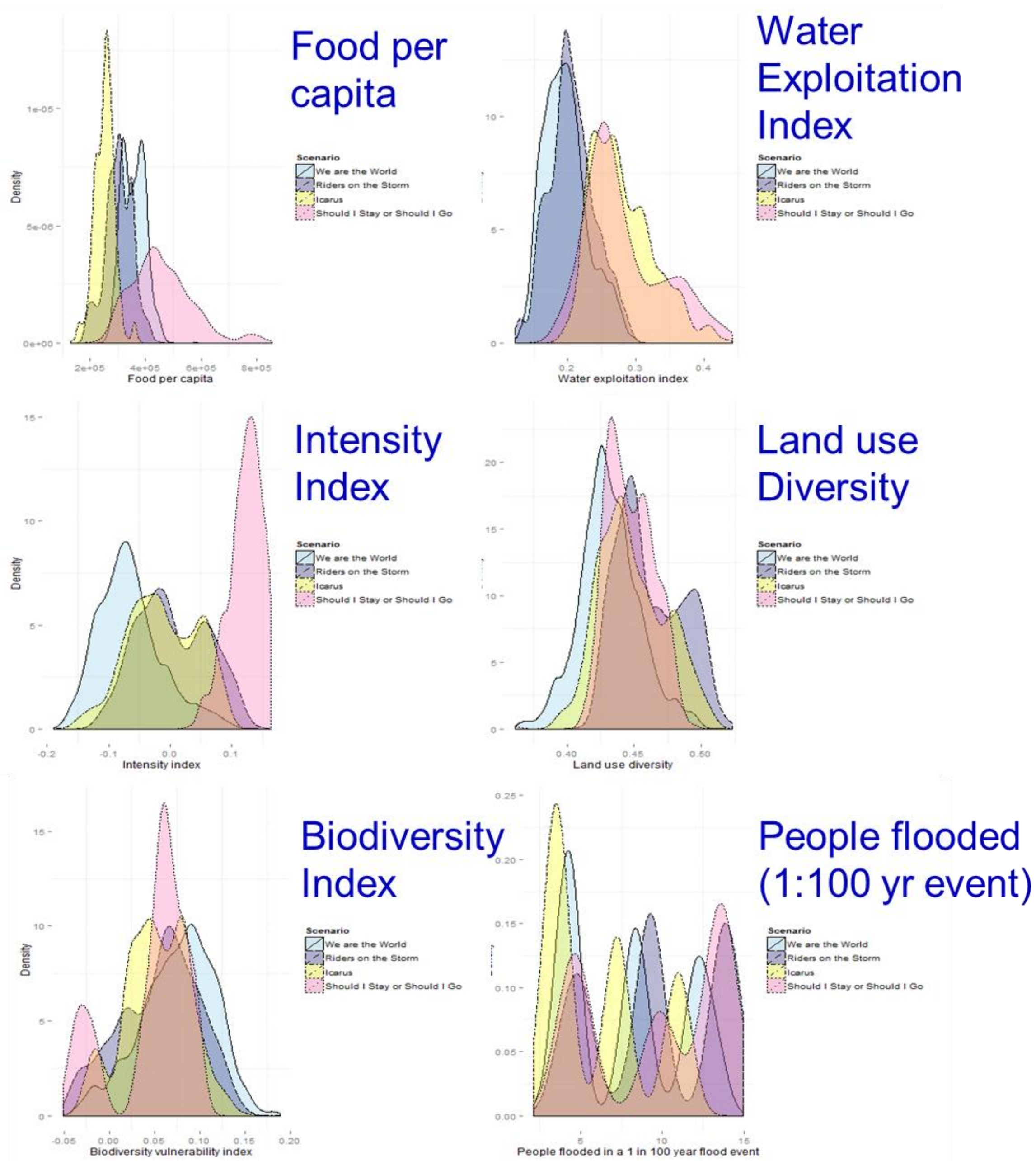

Figure 5.4: Conditional probabilistic futures of selected vulnerability indicators (after Brown et al., 2015).

6. Conclusions and timetable

This report has outlined a modelling framework for assessing the impacts of climate change under high-end scenarios in Europe. It comprises a multi-scale, integrated approach to assessment, focusing on case studies at global, European, national and sub-national scales. The conceptual basis of the study is a dynamic variant of the DPSIR framework developed by the European Environment Agency that explicitly accommodates adaptive management through a time dependent and iterative approach incorporating system feedbacks. In order to implement this approach, we have outlined a modelling strategy that comprises a set of six protocols involving: (i) the cataloguing of models; (ii) a review of past studies; (iii) model sensitivity analysis; (iv) scenario analysis; (v) evaluation of impact likelihoods; and (vi) uncertainty analysis. The protocols are being applied in the context of case studies at different geographical scales in close collaboration with, and guided by, sectoral and regional stakeholders.

A timetable for implementing the integrated modelling strategy is outlined in Table 6.1. Past studies with global models were reviewed ahead of the first EU External (central Asia) case study workshop in Kazakhstan in February 2015, and reviews of past studies with other models used in the project have been submitted by partners and are being compiled.

Table 6.1: Preliminary timetable of modelling studies in IMPRESSIONS (agreed January 2015). Stakeholder workshops for each case study are labelled WS.

Modelling study	Case study	Phase	Target	Deadline (DL)
Past studies	EU External*		WS 1 (EUx)	8 February 2015 (Internal DL)
Past studies	All case studies			31 March 2015 (Internal DL)
Sensitivity analysis	All case studies	Phase 1a	ECCA 2015	31 March 2015 (Internal DL)
Sensitivity analysis	All case studies	Phase 1b	Policy Event	31 July 2015 (Internal DL)
Scenario analysis	Europe	Phase 1	WS 2 (Europe)	February 2016 (WS 2)
Scenario analysis	Scotland	Phase 1	WS 2 (Scotland)	March 2016 (WS 2)
Scenario analysis	EU External*	Phase 1	WS 2 (EUx)	May 2016 (WS 2)
Sensitivity analysis	All case studies	Phase 2		Spring 2016 (Internal DL)
Scenario analysis	Hungary	Phase 1	WS 2 (Hungary)	June 2016 (WS 2)
Scenario analysis	Iberia	Phase 1	WS 2 (Iberia)	September 2016 (WS 2)
Likelihood of impacts	All case studies			Autumn 2016 (Internal DL)
Scenario analysis	Europe	Phase 2	WS 3 (Europe)	February 2017 (WS 3)
Scenario analysis	Scotland	Phase 2	WS 3 (Scotland)	March 2017 (WS 3)
Scenario analysis	EU External*	Phase 2	WS 3 (EUx)	May 2017 (WS 3)
Scenario analysis	Hungary	Phase 2	WS 3 (Hungary)	June 2017 (WS 3)
Scenario analysis	Iberia	Phase 2	WS 3 (Iberia)	September 2017 (WS 3)
Systematic uncertainty analysis	All case studies			Autumn 2017 (Internal DL)
Model inter-comparison	All case studies			Autumn 2017 (Internal DL)

* EU External refers to the case study in Central Asia on indirect impacts for Europe.

The sensitivity study is organised in two phases. Phase Ia is for models that already exist which could apply the protocol in spring 2015. The finalised protocol was circulated to all modellers in December 2014 with a request to complete initial model simulations by spring 2015, targeting the ECCA 2015 Conference organised in Copenhagen, Denmark in May 2015. Final results should be provided by the end of July 2015 (Phase 1b), ahead of a policy event on high-end climate change in Brussels in September 2015. Phase 2 of the sensitivity study is for models currently under development, with which the exercise can be conducted once the models have been developed.

Work on the likelihood of impacts is due to proceed during 2016, with systematic uncertainty analysis and model inter-comparison to be undertaken following the completion of the two phases of scenario analysis (see section 5.5). Phase 1 of the scenario analysis feeds into the second set (WS2) and Phase 2 into the third set (WS3) of stakeholder workshops for each case study (Table 6.1).

7. Acknowledgements

We are pleased to acknowledge colleagues in the IMPRESSIONS project (too numerous to mention by name here) who have provided input and feedback contributing to the development of the integrated framework. This includes all respondents who completed the modelling questionnaire and data dictionaries as well as attendees of two modelling workshops – held at the London School of Hygiene and Tropical Medicine in April 2014 (graciously facilitated by Dr Sari Kovats) and at the Scuola Superiore Sant'Anna, Pisa in September 2014 (kindly facilitated by Dr Andrea Roventini). Inputs were also received from participants of relevant sessions at the two IMPRESSIONS General Assembly meetings (Oxford, January 2014 and Barcelona, January 2015) and at other IMPRESSIONS case study workshops. Details of these meetings can be found on the IMPRESSIONS website.

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Annex A: Review of past studies

The aim of the report is to give an overview of model behaviour under high-end scenarios (HES) according to findings from past studies and existing model runs that have been conducted using the model that is being applied in IMPRESSIONS. The subsequent sections provide a template for modellers to follow.

1. Introduction

In this section give a short introduction to the model and its application in particular with respect to climate change studies.

2. Specification of past studies

In this section give a short description of past studies where your model has been applied to examine high-end scenarios (HES). Give the references of the studies and the key characteristics of the scenarios applied in the studies in Table A1 according to the examples given. High-end climate scenarios are likely to be found among those climate model outputs for the end of the 21st century based on emissions scenarios at the high end of the range (e.g. SRES A1FI or A2) or based on radiative forcing scenarios such as RCP8.5.

Table A1: Types of high-end scenarios examined.

Type of scenario variables examined	Geographical scale	Climate scenario (e.g. SRES A1FI/A2, RCP8.5)	Socio-economic scenario (e.g. SRES A1/A2, SSP3/5)	Time horizon of scenarios	Magnitude of change	Reference
climate	Scotland	SRES A1FI	--	2071-2100	Monthly temperature up to +8°C; Monthly precipitation from -5% to +55%	1
climate/population	Hungary	SRES A1FI	SRES A1	2071-2100	Summer temperature up to +7.2°C; population projections for Hungary (2100) from IPCC DDC scaled to Budapest	2

3. Quantitative description of findings

Are model responses explainable?

- Describe model behaviour towards the high-end of the scenario range;
- If applicable, list any model quirks or deficiencies exposed by such analysis.

Give concrete examples of results in quantitative terms.

Use the citations given in Table A1 to identify studies where necessary.

Example 1: Under the SRES A1FI HadCM3 and ECHAM 4 climate scenarios for 2071-2100 the mean annual temperature change over the study region (Scotland) was about +5.2 and +4.5 °C and annual precipitation increases by 23 % and 41 %, respectively. Impacts of these changes (monthly adjustments) on runoff in the Tay catchment were estimated using the INFALLible hydrological model, and showed increases varying between +32 and +56%, depending on scenario and parameter selection of the hydrological model[1]

or

Example 2: Under the SRES A1FI HadCM3 and ECHAM 4 climate scenarios for 2071-2100 the mean summer temperature change over the study region (Hungary) was about +7.2 and +5.5 °C, respectively. Impacts on heat-related mortality among the elderly in Budapest, using a temperature-based, exponential mortality model (EXTRAPerLATE), suggest that annual mortality during the warmest years at the end of the century could exceed 150,000-200,000 persons over the age of 70 by 2100[2]

4. Qualitative description of findings

Do model responses appear to be plausible?

From a qualitative point of view :

- Do model responses conform to expectations under HES?
- If applicable, explain any aspects of model behaviour that are difficult to explain.
- On the basis of this analysis, describe any model features that might require refinement.

Use the citations given in Table A1 to identify studies where necessary.

Example 1: The INFALLible model has been run for a range of future climatic conditions, and responses appear to be credible over this range. ....

or

Example 2: The EXTRAPerLATE model appears to provide over-estimates of the mortality rate among the elderly population at high temperature changes. For scenarios of modest temperature increases (<0.5°C), changes in mortality appear more credible. The over-estimates are probably due to the exponential form of the statistical fit versus observed data during the baseline period, and spurious extrapolation of the relationship to temperature conditions well outside historical experience. The model developer has since died (in a heatwave), and a replacement was identified only recently. The model is now under revision using a refined method and we expect to test it by the end of 2015 .....

5. Impacts of high-end scenarios

What are the most notable impacts and important outcomes that emerge under HES?

Was an uncertainty analysis performed to inform about the robustness of the results? If so, what aspects of uncertainty were explored (e.g. model parameter uncertainty, structural or inter-model uncertainty, input variables including data, assumptions and scenarios)?

Use the citations given in Table A1 to identify studies where necessary.

6. Conclusions

7. Acknowledgements

8. References

Examples:

1. McFloe, O.O. (2008). Hydrological impacts of future climate change in the Tay catchment. Scottish Journal of Fly Fishing, 23: 33-45.

2. Forrófej, V. (2007). An exponential model of temperature-related mortality for Budapest. Unpublished manuscript, College of Emeritus Statisticians, Budapest (in Hungarian).

Annex B: Protocol for conducting a sensitivity analysis using the impact response surface approach

1. Introduction

An impact response surface (IRS) is a graphical device for plotting the modelled behaviour of an impact variable in response to changes in two key explanatory variables that span the x- and y-axes of the plot. A key benefit of the IRS method is that it is a systematic way of analysing the sensitivities of modelled impacts to changes in the variables being tested and provides impact estimates across a wide range of conditions. Figure B1 presents a typical IRS where the impact variable is plotted with respect to changes in annual precipitation and temperature.

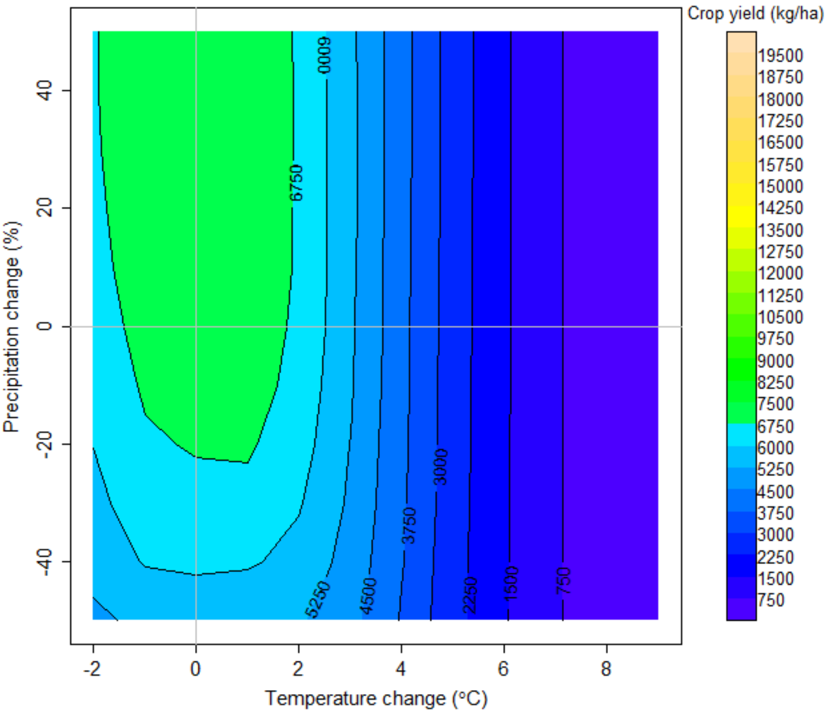

Figure B1: An example of a typical impact response surface, depicting the modelled response of grain yield (kg ha^{-1}) to changes in temperature and precipitation relative to the baseline climate (intersecting grey lines).

This document defines a protocol for a two-variable sensitivity analysis of an impact model, the results of which can be plotted as an IRS. It is anticipated that this protocol will be applied with several of the impact models in IMPRESSIONS and that the outcomes may assist in summarising and comparing model behaviour across sectors and regions (cf. section 2.3.1 in this Annex). Results can also provide insights about possible discontinuities and thresholds in model responses that are dependent on the two variables of the sensitivity analysis (cf. Fronzek 2013).

This protocol defines a basic method with simplifying assumptions (e.g. no seasonal cycle in change in climate variables). The method has so far been applied in the context of changes in climatic explanatory variables, but responses to non-climate variables can also be examined. A further application of the IRS method is to add elements to the basic method to improve the realism of the model simulations and to combine the resulting IRSs with probabilistic projections for the same two variables. This combined method enables estimates to be made of the likelihood of a certain specified impact occurring. Impacts can then be assessed within a quantified risk framework. The combined method was developed in the EU FP6 ENSEMBLES project, with case studies from various sectors. The principles of the method are described in Fronzek et al. (2010) in a case study on permafrost features. Other case studies using crop (Børgesen and Olesen, 2011; Ferrise et al., 2011) and hydrological models (Weiss, 2011; Wetterhall et al., 2011) have also been presented. The combined method is discussed in a separate protocol that is currently under development for estimating the “Likelihood of impacts”.

2. Sensitivity of an impact variable to changes in two drivers (basic method)

The sensitivity of an impact variable (Z) to changes in two key drivers (X and Y) is tested by modifying values of baseline data of X and Y (for a reference date or period) over systematic increments so that the changes span the range of changes projected for the future period of interest.

2.1. Model simulations for constructing IRS

The elements listed under this heading have to be decided upon by the modeller(s) according to the guidance given and in the context of decisions made in the project. Model input parameters and other aspects not defined here are chosen to represent baseline conditions and are kept fixed throughout the perturbations to X and Y. By keeping all other variables fixed while changing only two key drivers (X and Y), the sensitivities can be analysed similarly everywhere without introducing additional dimensions to the analysis.

2.1.1. Key impact variables of interest

Modeller’s choice:

- Key output variable(s) of an impact model is/are chosen (Z), e.g. run-off, mortality, crop yield. Several output variables can be chosen, if relevant, and the results for them reported in the same output file. For presenting the results, each variable is plotted on a separate IRS.
- The variables that are chosen should represent something that is easily interpretable.
- It is beneficial if the output variables are presented using metrics that can be used for inter-comparison with other models.

2.1.2. Drivers

Modeller’s choice:

- Two key drivers (X and Y) are chosen, e.g. temperature and precipitation.
- If drivers other than temperature and precipitation are chosen for the analysis (climatic or non-climatic), the IRS core group should be consulted for information on how to apply specific rules to adjust the baseline values (e.g. we may decide that radiation should be adjusted only on rain days, and climate experts may need to be consulted to estimate baseline and projected rain-day radiation).

2.1.3. Baseline years

A common baseline period for climate and a baseline socio-economic year have been set to be used in IMPRESSIONS. These should be used for the simulations and all perturbations of X and Y made with respect to the baseline values.

- Baseline period for climate: 1981-2010
- Baseline socio-economic year: 2010

If a combination of a climatic driver (baseline 1981-2010) and socio-economic driver (baseline year 2010) is used for the simulations, socio-economic data of 2010 is used in combination with each climatic baseline year (1981 and 2010, 1982 and 2010, etc.). Modellers should consult with the IRS core group if this procedure is not feasible.

2.1.4. Temporal resolution of data

Modeller’s choice:

- The impact model is run at its normal time resolution (e.g. daily, monthly).

2.1.5. Spatial resolution of data

- The impact model is run at its native resolution, e.g. point, grid, region.
- Models run for **Europe**:
    - The aim is to produce aggregate results to represent the sensitivity of the output variable for eight different sub-regions of Europe following Rockel and Woth (2007). Coordinates defining the boundaries of each of the eight sub-regions for which aggregate results should be provided for are listed below in Table B1 and shown in Figure B2. Minor revisions have been made to the original regional specifications to cover small gaps at the edges of sub-regions. Sub-region 6 is extended to the eastern border of sub-region 8, while sub-region 7 is extended to the east to cover parts of Bulgaria not covered by the original regions.
    - Various options for dividing Europe into sub-regions were considered including the regions used in CLIMSAVE and those defined by Metzger et al. (2005). To keep the option open to extend the IRS approach to include estimation of likelihoods of future impacts, the regions should be defined so that probabilistic projections of X and Y would be available. While each option has its benefits, the use of the Rockel sub-regions is supported by them being widely known and used in climate research and more importantly because probabilistic projections of temperature and precipitation are readily available for these regions (see Harris et al., 2010). The rectangular shape of the regions provides further benefits that simplify the approach.
    - In case a model is simulating variables that can be used for inter-comparison with the regional case study models, modellers are additionally asked to provide aggregate results for the case study regions (Iberia, Hungary, Scotland, as relevant). The groups working with the regional case studies have to be consulted to agree on the regions that the simulations should be performed for to make sure that the regions are comparable.
    - Regional aggregation should be performed in a sensible way. For models operating on a grid, this could be the average, minimum and maximum values of a chosen number of grid boxes for each region. For a hydrological model simulating catchment-scale responses, representative catchments could be selected for each region.
- Models run for the **regional case studies** (Hungary, Scotland, Iberia):
    - Modellers are asked to provide aggregate results for the region that is relevant for the regional case study, e.g. for Iberia, results could be for a single catchment.

Modeller's choice:

- It is up to the modellers to decide how many points/grid boxes/regions/catchments/basins within each region are run to produce a representative result for each region.

Table B1: Coordinates (decimal degrees) of the corner points of each of the eight European sub-regions.

ID	Sub-region	West	East	South	North
1	British Isles	-10	2	50	59
2	Iberian Peninsula	-10	3	36	44
3	France	-5	5	44	50
4	Central-Europe	2	16	48	55
5	NE Europe	5	30	55	70
6	Alps	5	15	44	48
7	Mediterranean	3	25	36	44
8	East-Europe	16	30	44	55

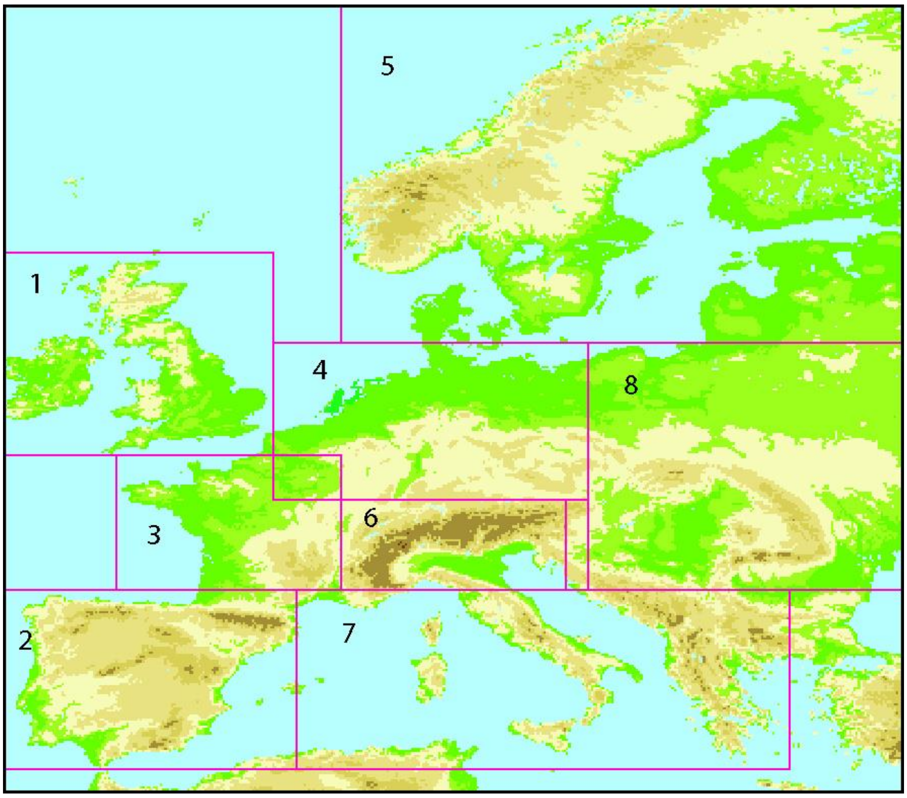

Figure B2: European sub-regions by Rockel and Woth (2007). Source http://ensemblesrt3.dmi.dk/.

2.1.6. Ranges and increments of the changes to the baseline values

- Simulations need to be conducted for each combination of changes in X and Y. Ranges used to perturb X and Y and the interval of the increments between the ranges are set to follow a common protocol.
- Ranges used for perturbing the drivers (e.g. temperature is perturbed between -1°C and +11°C relative to the baseline) are given in Table B2 for models run for **Europe** and in Table B3 for models run for the **regional case studies** (columns *Min* and *Max*) for temperature, precipitation, population and GDP.
    - Although, the sensitivity analysis itself is scenario neutral, it is beneficial to define the range of changes on the basis of projected high-end changes.
    - The range of changes in temperature and precipitation is defined to accommodate the range of probabilistic projections of Harris et al. (2010) until the end of the

century which typically extend outside climate model projection ranges. For temperature, the range starts from -1°C as the lowest percentiles give a slight decrease in temperature for Scandinavia for the earlier time periods.
    - As the probabilistic projections of temperature and precipitation are different for each Rockel sub-region the required ranges would also differ from one sub-region to another. Using varying ranges for different parts of Europe when performing simulations for Europe causes additional complications while performing the simulations and when presenting the results. To simplify the approach, a range wide enough to accommodate the changes projected throughout Europe is used for all simulations for **Europe**. For the **regional case studies**, region specific ranges of relevant Rockel regions for each case study (British Isles (1) for Scotland, Iberian Peninsula (2) for Iberia and East-Europe (8) for Hungary) are used, as the intention is not to compare results of different regions.
    - Ranges of perturbations for other variables than temperature and precipitation, such as population and GDP, need to be defined to accommodate projected high-end changes across Europe. Sources for population and GDP could be the IMPRESSIONS scenarios (if already available), the ranges used in the CLIMSAVE IAP or the SSP projections[2]. For example, baseline population or GDP (as purchasing power parity) could be modified to cover the range of changes across all SSPs until the end of the century. An example of the values across Europe is given in Table B2 and for the regional case studies in Table B3 where values for Iberia cover the ranges projected for Spain and Portugal and United Kingdom is used for Scotland. CLIMSAVE IAP used ranges of -50% to +50% for population and -20% to 200% for GDP, but the time horizon there was until mid-century.
- The intervals for the perturbations (e.g. in 1°C intervals between the specified ranges: 0,1,2,3 etc.) are specified in Table B2 for models run for Europe and in Table B3 for models run for the regional case studies (column *Interval*).
    - The increments are not of equal interval in all cases to reduce the amount of simulations required. Temperature is perturbed in smaller steps closer to the baseline.

Table B2: Range and increment of perturbations for simulations for Europe. Within the range defined by the minimum (Min) and maximum (Max) change to drivers, the baseline values of the driver are perturbed in defined intervals (Interval). The resulting sequence of perturbations to each driver is listed in column "Sequence". Values to be determined are labelled t.b.d.

Driver (X or Y)	Min	Max	Interval	Sequence
Temperature	-1°C +5°C	+5°C +11°C	1°C 2°C	-1,0,1,2,3,4,5,7,9,11 (°C)
Precipitation	-60%	40%	10%	-60,-50,-40,-30,-20,-10,0,10,20,30,40 (%)
Other climate variables	t.b.d.			
Population (example ranges approx. covering the SSP ranges across Europe)	-90%	+210%	30%	-90,-60,-30,0,30,60,90,120,150,180,210 (%)
GDP (example ranges approx. covering the SSP ranges across Europe)	0% +100% 300%	+100% +300% +700%	25% 100% 200%	0,25,50,75,100,200,300,500, 700 (%)
Other socio-economic variables	t.b.d.			

[2] Available as country averages at https://secure.iiasa.ac.at/web-apps/ene/SspDb/

Table B3: Range and increment of perturbations for simulations for the regional case studies. Within the range defined by the minimum (Min) and maximum (Max) change to drivers, the baseline values of the driver are perturbed in defined intervals (Interval). The resulting sequence of perturbations to each driver is listed in column "Sequence". Values to be determined are labelled t.b.d.

Driver (X or Y)	Min	Max	Interval	Sequence
Temperature				
Scotland	-1°C	+7°C	1°C	-1,0,1,2,3,4,5,7 (°C)
Iberia	-1°C +5°C	+5°C +11°C	1°C 2°C	-1,0,1,2,3,4,5,7,9,11 (°C)
Hungary	-1°C +5°C	+5°C +11°C	1°C 2°C	-1,0,1,2,3,4,5,7,9,11 (°C)
Precipitation				
Scotland	-15%	15%	5%	-15,-10,-5,0,5,10,15
Iberia	-60%	30%	10%	-60,-50,-40,-30,-20,-10,0,10,20,30 (%)
Hungary	-30%	30%	10%	30,-20,-10,0,10,20,30 (%)
Other climate variables	t.b.d.			
Population				
Scotland	-30	120%	15%	-30,-15,0,15,30,45,60,75,90,105,120 (%)
Iberia	-45%	60%	15%	-45,-30,-15,0,15,30,45,60 (%)
Hungary	-60%	10%	10%	-60,-50,-40,-30,-20,-10,0,10 (%)
GDP				
Scotland	0% 200%	200% 1100%	50% 150%	0,50,100,150,200,350,500,650,800,950,1100 (%)
Iberia	0% 200%	200% 1100%	50% 150%	0,50,100,150,200,350,500,650,800,950,1100 (%)
Hungary	0% 250%	250% 750%	50% 100%	0,50,100,150,200,250,350,450,550,650,750 (%)
Other socio-economic variables	t.b.d.			

2.1.7. Method of applying the changes to the baseline values

A simple change factors approach is used to apply the changes specified in Tables B2 and B3 as a constant change to the baseline values (daily/monthly, etc.) of climate drivers. For temperature, a constant change is added to all days of the year (or months in case of monthly time-step). For variables where the change is expressed in percentages, the relative change is applied similarly to all time-steps of the year. Changes in variables not mentioned here can be considered on a case-by-case basis.

2.2. Number of simulations

This section is for illustrating the way to calculate how many simulations are required to produce the required results. The number of simulations required is affected by the number of baseline years, number of perturbations to the drivers (through the combination of the width of the ranges and the number of intervals) and the number of sites (points/grids/regions etc.) that the simulations are performed for as each element is used as a multiplier when calculating the number of simulations.

In this example, for a model that is run using period mean data over the 30-year baseline period (1981-2010) the number of baseline years is considered here to be 1. Each combination of perturbations of the 30-year baseline climate requires an additional simulation. Hence:

<Baseline years> x <X-steps> x <Y-steps> x <Sites>

Example: 1 x 10 x 11 x 1 = **110**

For a model that performs the simulations on a year-by-year basis for each of the 30 baseline years the number of baseline years would be multiplied by 30 in the above calculation.

The combination in the above example and in Table B4 is required for one period mean IRS. A second site would require double the amount of simulations and produce a second period mean IRS as a result, and so forth as required (Table B4).

Table B4: Example of the number of simulations (N) required for performing the analysis for an individual IRS presenting long-term results across the baseline period (30 years) for one site.

					N
Baseline years	1981-2010 (as a period mean)				1
Perturbations	***Variable***	***Min***	***Max***	***Interval***	
	X	0	+5	1	*6*
		+5	+11	2	*3*
					10
	Y	-60	+40	10	11
Sites	One grid box (lat: 60.81, lon: 23.5)				1
Total number of simulations					1*10*11*1 = 110

2.3. Delivery and processing of simulation results

Output is submitted as a csv (comma separated) ascii file with all results in one file and one row per each combination of Region, Year, X and Y and optional columns of A,B,C etc. in case the full set of simulations has been conducted for different topic-specific options. For example, crop model outputs could include in column A the crop cultivar assumed in simulations, if more than one cultivar has been tested across the full set of simulations. Additionally the file should be headed by a "Metadata" section, where the definitions of X, Y and Z and A,B,C…are given, with as many columns for Z (Z1, Z2,...,etc.) as there are output variables being reported. In the "Free text" row(s), it is possible to specify other model options that were selected (CO_2 level, socio-economic assumptions, etc.) In case of missing values, for example failure in the simulation caused by a specific combination of changes (e.g. crop failure at high temperature increases), they should be marked as "na". The data section should start with a header row starting "Model,Reg,". When providing results for the European sub-regions the "Reg" (Region) should be one of the following: BI (for British Isles), IP (for Iberian Peninsula), FR (for France), CE (for Central-Europe), NE (for NE Europe), AL (for Alps), MD (for Mediterranean) and EA (for East-Europe). When providing results for the regional case studies the "Reg" should be one of the following: HU (for Hungary), SC (for Scotland) and IB (for Iberia). Note: "IP" is used for the European sub-domain Iberian Peninsula and "IB" for the simulations concerning the Iberian regional case study.

Alternatives for providing the output data, depending on what is meaningful:

- if a model is run on a year-by-year basis, results per year should be provided. In a typical baseline period of 30 years this gives results for 30 baseline situations (zero change to X and Y) and 30 results for each systematic adjustment to that baseline (can refer to the whole year, relevant season, etc.);
- if a model is run as a sequence of years over the entire baseline period, period mean results across the baseline years (e.g. 30-year mean) should be provided for the baseline and each systematic adjustment to the baseline;
- if a baseline socio-economic year is only considered, results for perturbations to that baseline year should be provided;
- if a combination of a climatic driver (baseline 1981-2010) and socio-economic driver (baseline year 2010) is used, results are provided for each climatic baseline year from 1981 to 2010 either on a year-by year basis or as period mean results over the climatic baseline period;
- other statistical moments describing the distribution of a 30-year sequence might also be of interest (e.g. standard deviation; skewness).

The results of Z should be provided as absolute values (e.g. kg ha^{-1}) and not, for example, as changes relative to the baseline.

Examples for providing results for individual years of the baseline period or over the entire baseline period are given below, and results in this format should be sent by email to Stefan.Fronzek@ymparisto.fi.

Output format for one row of results/ baseline year in a 30-year baseline period

----

Metadata:
A = crop cultivar; SW for Spring wheat, WW for Winter wheat
X = temperature change (°C)
Y = precipitation change (%)
Z1 = crop yield (kg/ha)
Z2 = total biomass (kg/ha)
Zn = up to the n^{th} output variable
Free text = CO_2 360 ppm

```
Model,Reg,Year,A,X,Y,Z1,Z2,Zn
ABC123,BI,1981,SW,0,-60,2200,3500,…
ABC123,BI,1981,SW,1,-60,2180,3800,…
ABC123,BI,1981,SW,2,-60,2000,4300,…
…
ABC123,BI,2010,SW,11,40,na,500,…
ABC123,IP,1981,SW,0,-60,1000,2000,…
…
```

Output format for period mean results over the 30-year baseline period

```
-------------------------------------------------------------------------------------------------------------------
Metadata:
A = crop cultivar; SW for Spring wheat, WW for Winter wheat
X = temperature °C
Y = precipitation %
Z1 = crop yield (kg/ha)
Z2 = total biomass (kg/ha)
Zn = up to the nth output variable
Free text = CO2 360 ppm

Model,Reg,Year,A,X,Y,Z1,Z2,Zn
ABC123,BI,1981-2010,SW,0,-60,3000,3500,…
ABC123,BI,1981-2010,SW,1,-60,2750,3800,…
ABC123,BI,1981-2010,SW,2,-60,3500,4300,…
…
ABC123,BI,1981-2010,SW,11,40,2000,500,…
ABC123,BI,1981-2010,SW,0,-60,1500,2000,…
…
-------------------------------------------------------------------------------------------------------------------
```

2.3.1. Example of the application of the results

In order to ensure consistency of presentation and analysis, Stefan Fronzek will be responsible for producing the IRSs of the results provided. For purposes of comparison, it may be necessary to standardise plots and/or to convert them to relative changes. These steps of the analysis will be carried out in close co-operation with modelling groups. The results of the analysis can be plotted as IRSs that visualise the sensitivity of the impact variable (Z) to changes in the two driving variables (X and Y). Sensitivities across different sectors and regions can be compared by plotting the results side by side (Figure B3).

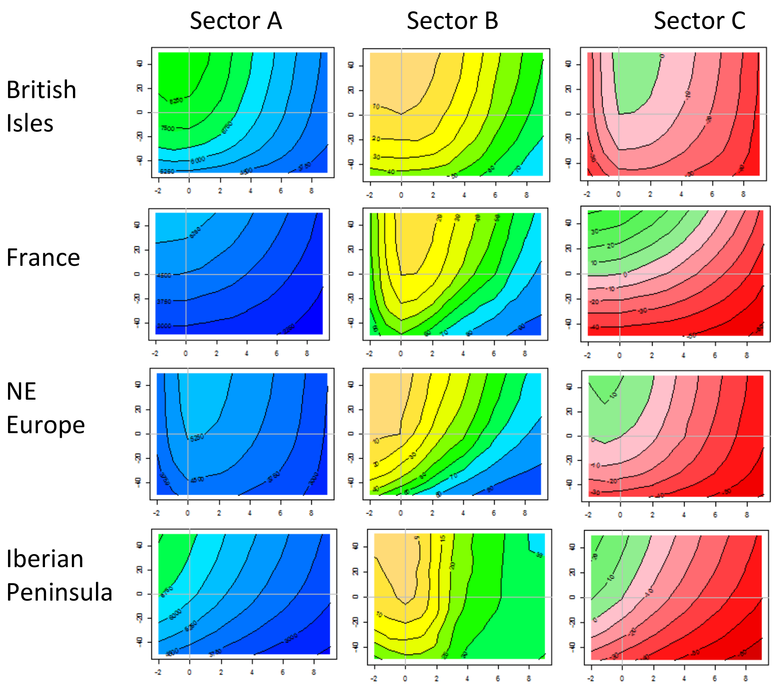

Figure B3: Dummy example presenting impact response surfaces of modelled impacts in different sectors for changes in two driving variables over sub-regions of Europe.

2.4. Secondary drivers

If variables other than the two key drivers are considered to be of crucial importance for the impact, we recommend that the full analysis be performed again for another combination of key variables (e.g. precipitation and radiation in addition to precipitation and temperature) and to report the results similarly. In this case the IRS core group should be consulted for information about applying specific rules for adjusting the baseline values (e.g. advising on how to adjust radiation values).

Alternatively a conventional one variable sensitivity analysis could be performed on each of the variables to provide additional information for interpreting the results of the IRS. The procedure for this would follow the specifics of the full sensitivity analysis but include only one variable. The ranges of changes would have to be defined to accommodate plausible ranges of high-end changes as probabilistic projections might not be available. An example of the output data format for providing one value per baseline year is given below.

Output format for one value / baseline year

```
------------------------------------------------------------------------------------------------------------------------
Metadata:
A = crop cultivar; SW for Spring wheat, WW for Winter wheat
X = radiation (kJ m-2 d-1)
Z1 = crop yield (kg/ha)
Z2 = total biomass (kg/ha)
Zn = up to the nth output variable
Free text = CO2 360 ppm

Model,Region,Year,A,X,Z1,Z2,Zn
ABC123,BI,1981,SW,0,3000,3500,…
ABC123,BI,1981,SW,1,3280,4100,…
,,,,,
ABC123,BI,2010,SW,11,1100,1700,…
ABC123,IP,1981,SW,0,2000,3400,…
------------------------------------------------------------------------------------------------------------------------
```

3. Status and timetable

At the General Assembly in Barcelona in January 2015, Table B5 was compiled which indicates the intentions of modellers to take part in the IRS analysis, the drivers (X and Y) they will test and their regions of application.

The study is organised in two phases. Phase Ia is for models that already exist which could apply the protocol in spring 2015. The finalised protocol was circulated to all modellers in December 2014 with a request to complete initial model simulations by spring 2015, targeting on the ECCA 2015 Conference organised in Copenhagen, Denmark in May 2015. Some initial analyses using previous sensitivity analyses conducted with the CLIMSAVE integrated assessment platform (IAP) were presented as IRS plots at the General Assembly meeting in Barcelona (January 2015). The next deadline that some groups wish to target is a policy event on high-end climate change in Brussels in September 2015. The aim should be to have results to present there. Thus, final results of Phase Ia should be provided by end of July 2015.

Table B5: Models applied in the IRS sensitivity analysis, driving variables to be tested and regions of application.

Model	Participation	Phase	X	Y	Regions
AIM/Impact[Health]	YES	1a	Temperature	Population	Europe
AIM/Impact[Water]	NO	-	-	-	-
M-GAEZ	YES	1a	Temperature	Precipitation	Europe
VISIT	YES	1a	Temperature	Precipitation	Europe
GLOBIO	YES	1a	Temperature	Precipitation	Europe
WaterGAP2	NO	-	-	-	-
iPETS	NO	-	-	-	-
Keynes+Schumpeter / ENGAGE	NO	-	-	-	-
Lagom Generic 2.0	?	-	-	-	-
LagomRegio 1.0	?	-	-	-	-
CRAFTY 1.0	YES	1b	Temperature	Precipitation	Europe
CLIMSAVE IAP	NO	-	-	-	-
rIAM	NO	-	-	-	-
SFARMOD	YES	1a	?	?	?
ForClim v3.3	YES	1b	Temperature	Precipitation	Europe
CFFlood	YES	1a	GDP?	Population?	Europe
WaterGAP meta model	YES	1a	Temperature	Precipitation	Europe
SPECIES	YES	1b	Temperature	Precipitation	Europe
RUG (Residential Urban Growth)	YES	1b	GDP	Population	Europe
Heat-related mortality	YES	1b	Temperature	Population	Europe, City, Global
SWIM	YES	1b	Temperature	Precipitation	Specific catchments
Aporia	YES	1b	Temperature	Precipitation	Scotland
LandClim v1.4	YES	1a	Temperature	Precipitation	Iberia
Lyme disease	YES	1b	Temperature	Precipitation	Scotland
Tourism model	YES	1b	Temperature	Precipitation	Scotland

Phase 1b is for models currently under development which could repeat the exercise once the models have been developed.

4. References

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Annex C: Scenario Analysis

1. Determining the scenarios to be applied

Scenario analysis is being undertaken in IMPRESSIONS is two phases. Phase 1 describes a set of scenario-based model simulations to be conducted ahead of the second set of case study stakeholder workshops (WS2) taking place during 2016. Phase 2 describes a revised set of model simulations (iterations) to be designed and carried out ahead of the third set of stakeholder workshops (WS3) in 2017, based on feedback from WS2.

This Annex focuses on introducing the IMPRESSIONS scenarios and outlining a draft set of modelling procedures for Phase 1 of the Scenario Analysis. Phase 2 modelling protocols will be outlined later in the project.

1.1. Types of scenarios selected in IMPRESSIONS

Two types of "scenario" are being applied in IMPRESSIONS case studies: descriptive or exploratory scenarios based on a global framework of integrated pathways, and normative scenarios developed in a participatory process with stakeholders. In WP2, sets of descriptive scenarios are being developed for all case study regions based on a global framework (Moss et al., 2010) of representative concentration pathways (RCPs – van Vuuren et al., 2011) and shared socio-economic pathways (SSPs - O'Neill et al., 2014; 2015). The RCPs define different assumptions about the levels of forcing of the climate system attributable to human activities. SSPs describe plausible alternative socio-economic developments that affect society's ability to ameliorate the forcing of the climate system and to adapt to changes in climate brought about by that forcing. Narrative storylines and quantifications of key variables (using integrated assessment models, fuzzy sets and expert opinion) are being developed for four very different development pathways (SSPs) in each case study region (WPs 2 and 6A). In IMPRESSIONS there is a particular focus on the high-end of the range of forcing described by RCPs, though low-end forcing is also considered, given its policy relevance in international climate negotiations.

Normative scenarios are also being developed in IMPRESSIONS (WP4), comprising visions of an equitable and sustainable future in each case study region and the pathways required to get there. These are idealised end points in 2100, which also explore the kinds of transformative systemic changes that might be required to achieve them.

The challenge for scenario analysis in the IMPRESSIONS project is to estimate how Europe's environment, economy and society may be affected by, and can respond to, climate change under alternative development pathways during the 21st century, and to explore the effectiveness of different options in steering regional development towards stakeholder-defined goals of sustainability and equity. In essence, the approach involves using models to simulate impacts resulting under different descriptive scenarios defined in WP2, and where these impacts are adverse, to explore options for diverging towards more sustainable solutions, using the normative scenarios developed in WP4.

Most of the discussion in this document refers to the descriptive scenarios, as these form the basis for initial scenario analysis with impact models. The analysis is designed to be iterative and transient, such that model outcomes during one time period may determine modelling assumptions made in a subsequent period. These assumptions may be consistent either with SSP descriptions (treated in initial reference simulations) or departures from these, defined by the normative pathways (see below).

1.2. Number of scenarios

The IMPRESSIONS project has selected four SSPs and two RCPs for application in scenario analysis (see Deliverable 2.1 for background and justification for the selection). Each pathway is represented by quantitative variables – SSPs by socio-economic and land use variables; RCPs by climatic, atmospheric composition and sea level variables. These variables are subject to uncertainties that also need to be considered in choosing the number of scenarios to be applied.

1.2.1. Shared socio-economic pathways (SSPs)

The four SSPs are as follows (O'Neill et al. 2015):

- SSP1: Sustainability –Taking the green road
- SSP3: Regional rivalry – A rocky road
- SSP4: Inequality – A road divided
- SSP5: Fossil-fuelled development – Taking the highway

Of the five SSPs originally defined by O'Neill et al (2014), only the intermediate case (SSP2) has been excluded here, as the focus on IMPRESSIONS is on high-end and low-end scenarios. Moreover, SSP2 is the only socio-economic pathway for which there is no direct analogue among the existing sets of scenarios already specified for the European region in the earlier CLIMSAVE project. The narrative storylines and quantifications of the four SSPs for each case study are being developed in WP2. Further information on the methodology and timetable for their development for each case study is provided in Deliverable 2.1

1.2.2. Representative concentration pathways (RCPs)

Two RCPs have been selected to embrace a range of forcings of the climate system from the highest forcing reported in literature on emissions (RCP8.5), down to a low-end forcing for which global climate projections can be identified that restrict global mean annual temperature change to as low as 2°C above pre-industrial levels (RCP4.5). A lower forcing (RCP2.6) has also been examined by climate modellers, but this level of forcing would require extremely ambitious reductions in greenhouse gas emissions during the 21st century, and there are few downscaled climate projections available for Europe based on this forcing.

1.2.3. Combining SSPs and RCPs

An initial selection of combinations of RCPs and SSPs was made at the IMPRESSIONS modelling meeting in Pisa (September/October 2014) and was subsequently refined at the General Assembly in Barcelona (January 2015). The combinations are depicted in Table C1. There are eight possible combinations, but only five of these are regarded as core scenario combinations (denoted as **XX**) to be considered by all modelling groups. The idea here is to be able to compare high-end climate projections (assuming RCP8.5) under two different assumptions of socio-economic development that assume high global challenges for mitigation (SSP3 and SSP5). One of these socio-economic futures (SSP3) can also be considered in combination with low-end climate projections (RCP4.5). Two different socio-economic futures associated with low global challenges for mitigation (SSP1 and SSP4) are considered alongside low-end climate projections (RCP4.5).

Table C1: Combinations of shared socio-economic pathways (SSPs) and representative concentration pathways (RCPs) selected for IMPRESSIONS. Red crosses are core combinations; blue circles are optional or infeasible combinations. Pathways extend to 2100.

	SSP1	SSP3	SSP4	SSP5
RCP8.5	o	XX	o	XX
RCP4.5	XX	XX	XX	o

SSPs assume no new climate policies, and the impact modelling analysis in IMPRESSIONS will investigate not only the impacts of combinations of RCP/SSP worlds, but also impacts assuming possible autonomous and policy responses (involving adaptation and mitigation), which can guide the integrated scenario outcomes towards sustainable and transformative pathways described in WP4. In the global modelling framework, such departures from the SSPs are referred to as shared policy assumptions (SPAs; Kriegler et al., 2014), though not all adjustments would need to be policy-driven. Sources of SSP scenario data for application in impact modelling are described in more detail in Deliverable 2.1.

1.2.4. Climate projections

RCP8.5 and RCP4.5 have both been applied as forcings for multiple ensemble simulations up to 2100 (or beyond) with global climate models during the fifth Coupled Model Intercomparison Project (CMIP5) exercise (Taylor et al., 2012). Some of those global model outputs have been downscaled to a finer resolution over Europe using statistical and dynamical methods. The CMIP5 model outputs have also been applied, in conjunction with other information on model uncertainties, to develop probabilistic climate projections using various techniques. All of this information on future climate and its uncertainties is available for application in IMPRESSIONS, so a selection procedure is necessary to define a manageable number of climate projections which also represent the high- and low-end of projections and capture other aspects of uncertainty (e.g. across variables and seasons). The following hierarchical scheme for identifying core and extended climate scenarios has been adopted (Figure C1). This comprises layers of information for guiding decisions, working from the outside inwards in Figure C1:

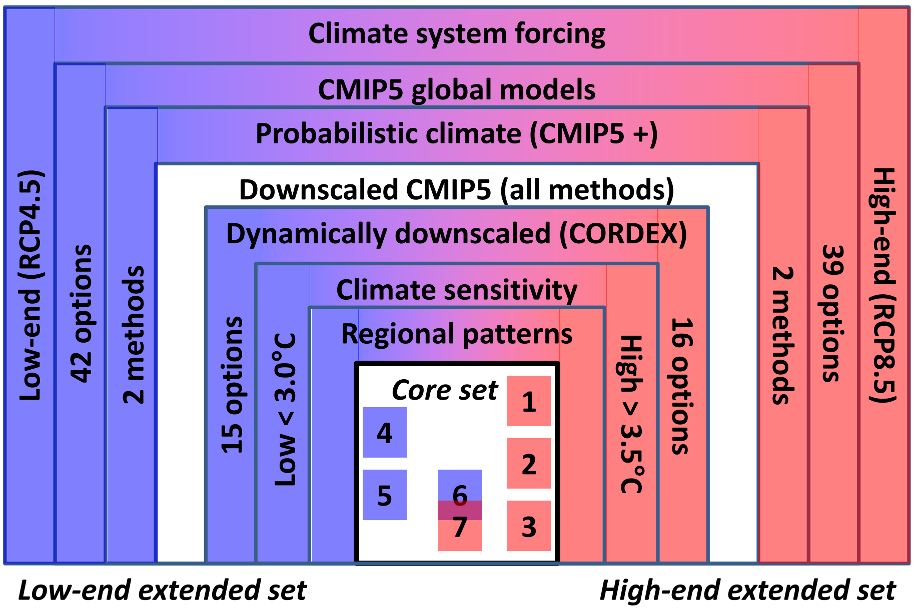

Figure C1: Criteria for determining core and extended sets of climate projections. Core projections are: I-3 (high-end), 4-5 (low-end) and 6-7 (intermediate). These are described in Deliverable 2.1.

1. Climate system forcing: IMPRESSIONS selected RCP8.5 at the high-end and RCP4.5 towards the low-end of emissions scenarios in the literature (radiative forcing by 2100 of 8.5 Wm^{-2} and 4.5 Wm^{-2}, respectively, relative to pre-industrial);
2. CMIP5 global models: simulations assuming a given forcing conducted for the CMIP5 exercise using different Earth system model (ESM) and coupled atmosphere-ocean general circulation model (AOGCM) simulations (single representative for each model);
3. Probabilistic climate: regional projections of temperature and precipitation change under a given forcing represented as joint probability distributions that account for uncertainties in projections from CMIP5 and other information (two methods used in IMPRESSIONS);
4. Downscaled (all methods): CMIP5-based projections downscaled to a finer resolution over Europe using statistical or dynamical methods (all available projections). CMIP5 models are typically screened to remove those with a large bias in representing present-day climate over Europe;
5. Dynamically downscaled (CORDEX): projections based on dynamical downscaling of CMIP5 global model outputs over Europe using fine resolution regional climate models (RCMs) as part of the Co-Ordinated Regional Downscaling EXperiment (CORDEX – Jacob et al., 2014). It was considered desirable to use dynamically downscaled climate projections for the core scenarios, since these should exhibit greater physical realism;
6. Climate sensitivity: The climate sensitivity is a measure of the modelled equilibrium global mean temperature response to a doubling of carbon dioxide in the atmosphere. Models which exhibit a high climate sensitivity typically project larger changes in climate than models exhibiting a low climate sensitivity. Here, only models with a climate sensitivity exceeding 3.5°C (at the upper end of the range) or lower than 3.0°C (lower end) were considered for the core set of climate scenarios;
7. Regional patterns: Maps of spatial and seasonal patterns of changes in precipitation (primary criterion) and temperature over Europe, used to guide the selection of a manageable number of projections showing a representative range of patterns.
8. Core set: The final selection of a core set of seven climate projections comprises:
    - at the high-end, three contrasting RCP8.5 projections with high sensitivity CMIP5 models downscaled using RCMs;
    - at the low-end, two contrasting RCP4.5 projections with low sensitivity CMIP5 models downscaled using RCMs; and
    - two intermediate projections downscaled with an RCM, one for high forcing (RCP8.5) with a low sensitivity CMIP5 model, a second for low forcing (RCP4.5) with a high sensitivity CMIP5 model.
9. Extended set: All IMPRESSIONS modelling groups are encouraged to apply the seven core climate projections in their scenario analysis. These are described in more detail in section 2.3 of this Annex. In addition, there are many other projections available for researchers to apply in an "extended set" of projections (coloured areas in Figure C1). For example, impact modellers may wish to simulate impacts of climate changes described by the full set of CMIP5 projections from global climate models. They may also wish to apply probabilistic climate projections in conjunction with impact response surfaces to estimate impact likelihoods (cf. Section 5.4).

1.3. Reference date/period (current baseline)

The reference or base year for socio-economic data in IMPRESSIONS is 2010, which is the latest year for which historical statistics are available on the IIASA database hosting the SSP projections. This contrasts with 2000, which was used (in the majority of cases) for the earlier CLIMSAVE project (Kok et al., 2014). The climatological baseline to be used is the most recent standard 30-year observational period, 1981-2010 (in contrast to 1961-1990 used in CLIMSAVE – Dunford et al., 2014).

Hence the base year for socio-economic data (2010) coincides with the final year of the climatological baseline. For those models requiring atmospheric carbon dioxide concentration as an input, the reference for this is fixed as the concentration mid-way through the climatological baseline in 1995: 345 ppm. However, some models may require annual historical concentrations as an input, which can be obtained from Annex II, Table AII.1 in IPCC (2013). Note that the concentration in 2010 was 388 ppm.

1.4. Time horizon

The time horizon for projections in the IMPRESSIONS project is 2100. For models that include time dependency (transience), scenario information will be required for years or period-averages of years between 2010 and 2100. Three standard 30-year periods have been selected as time windows for reporting results: 2011-2040, 2041-2070 and 2071-2100. Some modelling groups will apply 10-year mean or overlapping 30-year mean climate data in decadal simulations. The final definition of time periods for transient scenario runs is still under discussion with WP2.

2. Phase 1: Initial scenario analysis supporting the second case study stakeholder workshops

2.1. Objectives

The central objective of Phase 1 of the Scenario Analysis is to undertake an initial climate change impact, adaptation and vulnerability (CCIAV) assessment using relevant model simulations for each case study that can inform discussions at the second set of stakeholder workshops (WS2) scheduled during 2016 (see Table 6.1 in the main document). The five specific aims of these simulations are:

1. To **establish present-day impacts and vulnerabilities** for key output variables in the case study region that are representative of the current baseline period (up to 2010), using baseline climate and socio-economic input data and other relevant baseline assumptions.
2. To **estimate future impacts and vulnerabilities** under high-end and other scenarios for key output variables in the case study region out to 2100, assuming no explicit adaptation, by perturbing the baseline input data according to the five feasible combinations of RCP-based climate projections (core projections) and SSP-based socio-economic projections shown in Table C1.
3. Where feasible, to **simulate the effectiveness of explicit adaptation measures** in ameliorating impacts and vulnerabilities in the case study region during the period to 2100.
4. If possible, to **improve the representation of uncertainties** in projections by undertaking model simulations for an extended scenario ensemble.
5. To **deliver model outputs** in a consistent format for interpretation, possible comparison and eventual dissemination in the case study workshops.

These are outlined in more detail below.

2.2. Modelling baseline impacts and vulnerabilities

In advance of the analysis described here, the validity of models for simulating impacts of high-end scenarios in IMPRESSIONS is being evaluated in two ways. Protocols have been developed for reviewing past simulation studies (see section 5.2) as well as for undertaking model sensitivity analyses under a large range of changed conditions (section 5.3). This should provide a firm basis for proceeding with the baseline analysis described in this section.

Modelling of the current baseline serves several important purposes, though details vary between model types. First, it is a test of the model's performance in representing present-day conditions. Depending on the type of model being applied, simulations of present-day conditions (i.e. based on recent historical observations) can offer a possibility to compare simulated impacts in response to fluctuations in important driving variables such as weather, management and economic factors with observed impacts on key outputs of interest over the same period. Examples include inter-annual variations in responses of variables such as vegetation productivity, river discharge, land allocation, crop yield, farm revenue or heatwave mortality. This is a basic element of model testing (often referred to a model "validation"), and is needed to demonstrate the credibility of the model for application in a given case study region and situation. In some cases, where a model emulator is being applied, the original model from which it has been developed will need to have been tested in the same manner. Outputs from emulators often represent time-averaged, aggregate values, and some effort will be required to match these to equivalent aggregated observational data.

Second, an extended-period model simulation for present-day conditions may also be required for establishing an equilibrium between model outputs and major drivers, especially where modelled systems involve time lags (model "spin-up"). This may be important for some economic and agent-based land use models as well as dynamic vegetation models.

Third, the current baseline defines present-day conditions with which future estimates will be compared. It is the reference case for evaluating the likely impacts of future changes in climate and other drivers as well as the effectiveness of adaptation and mitigation responses. Bearing in mind the close scrutiny of results to be expected from regional stakeholders, the credibility and legitimacy of the modelling exercises will rest heavily both on the representativeness of baseline input data as well as the realism of present-day impacts and vulnerabilities to key driving variables.

As such, modellers need to pay special attention to the quality and representativeness of the input data being used to define baseline conditions as well as to the validity of the model outputs that will be the basis for the assessment of future impacts and effectiveness of adaptation measures. The dates and periods selected for representing baseline conditions in IMPRESSIONS are described in section 1.3 of this Annex, and detailed in Deliverable 2.1. Specifically, datasets that are of relevance as inputs for modelling purposes are:

- Climatological baseline: 1981-2010. Sources of site and gridded data at daily, monthly, seasonal, annual time steps are described in Deliverable 2.1. The applicability of some of these datasets is under review.
- Socio-economic statistics: base year 2010. Sources of data at spatial scales ranging from large world regions, through national to administrative regions and gridded are needed. Care is needed that these baseline data match model-based projections extending forwards from 2010. In some cases, recent observations from 2011 to present can be used as a reality check of near-term projections.
- Other model input data should be consistent with the baseline climate and socio-economic information. Standard sources of such information were specified by modellers when compiling the data dictionaries (see section 3.2).

2.3. Core modelling of future impacts and vulnerabilities

For modelling future impacts and vulnerabilities, the number of scenarios adopted and methods of scenario application are largely dependent on the type of CCIAV model being deployed. These are treated here in turn.

2.3.1. Number of scenarios

The socio-economic and climate projections adopted in IMPRESSIONS and the rationale for their selection were introduced in Section 1 of this Annex and are further described in Deliverable 2.1. In combination these can be regarded as "scenarios", though other elements such as dynamic feedbacks and policy adjustments may be required if these are to be regarded as truly integrated scenarios (e.g. see discussion in Chapter 5 of Deliverable 2.1).

At a minimum, it is expected that all modelling groups would conduct multiple simulations for the five RCP/SSP combinations shown in Table C1, including the core climate projections indicated in Figure C1. Table C2 summarises these combinations and provides a suggested order of precedence for conducting simulations. The logic of this choice is first, to treat the two scenarios that feature high-end RCP-based climate forcing (RCP8.5), but with pathways of global socio-economic development that both assume high fossil fuel emissions, but offer radically different views of vulnerability to climate change (high for SSP3; low for SSP5). Second, in contrast, is a world with low forcing of the climate (RCP4.5) and socio-economic development that favours low greenhouse gas emissions and an equitable distribution of resources leading to low vulnerability. Third, are two scenarios that combine unequal world development and high vulnerability with a relatively low forcing of the climate, including a variant of SSP3 that retains the same high vulnerability but produces lower forcing than scenario 1, and SSP4 which is an alternative vision of high vulnerability to SSP3 for an equivalent climate forcing.

Table C2: Five combinations of socio-economic (SSP-based) and climate (RCP-based) projections to 2100, in suggested rank order, for application in model scenario analysis. Short descriptors of global SSPs are from O'Neill et al. (2015). Climate projections are as shown in Figure C1. All modelling groups are encouraged to apply the core GCM/RCM projections (see Deliverable 2.1 for specific details of the chosen GCM/RCM combinations).

Priority	Socio-economic projections		Climate projections		
	SSP	Short descriptor	RCP	Core GCM/RCMs	Extended
1	SSP3	Regional rivalry	RCP8.5	1, 2, 3, 7	39 * GCM; 12 * RCM
2	SSP5	Fossil-fuelled development	RCP8.5	1, 2, 3, 7	39 * GCM; 12 * RCM
3	SSP1	Sustainability	RCP4.5	4, 5, 6	42 * GCM; 12 * RCM
4	SSP3	Regional rivalry	RCP4.5	4, 5, 6	42 * GCM; 12 * RCM
5	SSP4	Inequality	RCP4.5	4, 5, 6	42 * GCM; 12 * RCM

2.3.2. Methods of scenario application

The methods used to apply scenarios in model-based analysis depend on the spatial and temporal input requirements of the models and on the approach used in simulating impacts of changing conditions into the future (static time slice versus time dependent). These model requirements are detailed in the data dictionaries reported in Section 3.2. Each modelling group needs to make choices concerning how projections are to be represented in comparison to baseline input data. Climate projections commonly require adjustment to account for biases in representing present-day climate, either by applying the modelled change in climate as adjustments to baseline observations (change factors), or by adjusting the model outputs themselves to correct for the bias relative to observations (bias correction). These issues are being assessed by WP2 to provide advice to the CCIAV modellers on the most appropriate methods to use whilst maintaining as much consistency across the project as possible (see Deliverable 2.1). Other procedures are being developed to prepare baseline and projected population statistics at a spatial resolution suitable for application with CCIAV models. Some hypothetical examples of the kinds of choices that might be required are presented in Table C3.

Table C3: Examples of data input requirements, methods of applying future projections, representation of adaptation and sample outputs from scenario analyses using four hypothetical CCIAV models operating at different scales.

	Model 1	**Model 2**	**Model 3**	**Model 4**
Case study scale	Global	Europe	National	Catchment
Model resolution	Monthly/grid	Monthly/grid	Daily/grid	Daily/grid
Socio-economic projections				
Base case (2010)	GDP, population	GDP, population,	Population age structure	Population
SSP temporal resolution	Annual (trend)	Annual (trend)	Annual trend	Annual (trend)
SSP spatial resolution	National	Grid	Administrative	Grid
Climate projections				
Baseline(1981-2010)	Observed / reanalysis gridded	Observed / reanalysis gridded	Observed gridded	Modelled or observed historical
Time interval into the future	Static time slices: 2011-2040; 2041-2070; 2071-2100	Decadal: 2020-2100 using 30-year means	Decadal: 2020-2100 using 30-year means	Annual: 2011-2100
Projection data applied	RCM changes applied to baseline	RCM changes applied to baseline	RCM changes applied to baseline	RCM direct outputs
Adjustment method	Change factors	Change factors	Change factors	Bias correction
Other projections	CO_2 level: 2025; 2055; 2085	Oil price	Surface ozone (annual trend)	CO_2 level: annual 2011-2100
Adaptation	Explicit	Explicit	Explicit	Autonomous/ explicit
Sample outputs				
Maps/tables	Absolute values; change from baseline	Absolute values; change from baseline	Absolute values; change from baseline	Absolute values; change from baseline
Comparative graphs	Scenarios 1-5; adaptation effect	Scenarios 1-5; adaptation effect	Scenarios 1-5; adaptation effect	Scenarios 1-5; adaptation effect
Aggregate statistics	World regions or national	European regions	Administrative or national	Catchment average
Uncertainties	Box/whisker plots; PDFs	Box/whisker plots; PDFs	Box/whisker plots; PDFs	Box/whisker plots; PDFs

2.4. Modelling future adaptation

CCIAV models differ in their representation of adaptation responses to climate variations and change. Some models include such responses implicitly, as autonomous adjustments. Examples include the release of water downstream from reservoirs as a management action triggered by high water levels, or early sowing of crops by farmers following mild weather conditions in the spring. Other responses to changing climate conditions are included as explicit options in models. For instance, substitution of a cereal cultivar for another that is better suited to warmer conditions can be simulated by adjusting the phenological parameters of a crop growth model, or the parameters of a regional heat stress mortality model might require adjustment over time to resemble parameters currently applied in warmer regions, as populations become more accustomed to higher temperatures. Table C3 includes an entry for adaptation simply to indicate that modellers should explore adaptation options in their simulations during Phase 1 of the scenario analysis.

2.5. Exploring uncertainties using an extended scenario ensemble

If modellers have the interest and capacity to apply additional climate projections, there are sets of additional downscaled RCM projections available for application, as well as much larger sets of GCM-based projections from the CMIP5 archive (Table C2, final column and see Figure C1). An advantage of applying ensemble simulations, based on a large number of climate projections, is that uncertainties in future impacts and vulnerabilities attributable to future climate projections can be explored, and model outputs expressed in terms of frequency distributions.

2.6. Analysing and interpreting model outputs

The results of the Phase 1 scenario analyses are intended as inputs to a series of case study workshops (WS2) in which they will be interpreted and discussed with stakeholders. To assist this process, it is important that the results be presented in a clear and straightforward manner, along with representation of their uncertainties, so that key messages of the analysis can be conveyed effectively. Some ideas for presenting model outputs are illustrated in the bottom four rows of Table C3.

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