Specification for European model improvement and development

Deliverable D3B.1

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

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Preface

The European Commission-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 deliverable reports on the specification for model improvement and development within three of the sub-tasks for the European Case Study of IMPRESSIONS. The contribution to Task 3B.1 describes the further development of a regional integrated assessment model (rIAM) for Europe which will allow time-dependent modelling of impacts, adaptation and vulnerability within complex multi-sectoral linked system(s) in the face of multiple climate and non-climate pressures. Task 3B.2 describes the process-based impact modelling within Europe using the model SWIM (Soil and Water Integrated Model) which will help improve understanding of how any loss of information from using a simplified modelling approach (as in Task 3B.1) weighs against the gains in understanding of cross-sectoral interactions. Finally, Task 3B.3 describes the planned construction of a new agent-based model for Europe which simulates institutional behaviour through time with respect to climate change.

The specification for European model improvement and development links to 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 models. There are also links to WP1 for user needs and to WP4/5 in terms of exploring future visions, and in defining pathways of adaptive actions including transformative solutions.

Summary

This deliverable describes the specification for model improvement and development within the European Case Study of IMPRESSIONS. The agreed Vision for the European case study, which this deliverable supports, is:

> *"The ambition of the European Case Study is to develop new knowledge and evidence on the impacts of, and adaptation to, high-end scenarios (HES) on key ecosystem service indicators across Europe. Simulated changes in a range of urban, health, agricultural, forestry, water and biodiversity indicators over time under high-end climate and socio-economic scenarios will be used to help stakeholders and decision-makers develop long-term adaptation strategies for coping with HES.*
>
> *The case study will consider how impacts and adaptation responses in one 'sector' can have positive or negative effects in other sectors. The representation of adaptation decision-making in computer models will be improved to better understand how the effectiveness of adaptation under HES is influenced by timing and by socio-economic constraints. The insights gained through the stakeholder-led activities will provide capacity building for key decision-makers with respect to adaptive learning for coping with high-end scenarios".*

In contributing this vision for the Case Study, the objective for WP3B is to advance and apply European scale methods and models to better quantify and understand impacts, risks, vulnerabilities and adaptation options associated with a range of scenarios for key economic, social and environmental sectors and their cross-sectoral interactions. The deliverable describes how this objective will be achieved through the development of a range of modelling approaches (emulators; process-based; agent-based models) to provide better representation of dynamic time- and path-dependent impacts, adaptation and vulnerabilities:

- The specification for the regional integrated assessment model (rIAM) for Europe has been agreed, including the model grid resolution, the climatic and socio-economic baseline, the future decadal projection periods for the combined climate and socio-economic scenarios, the global boundary conditions, the addition of new sectoral models (health) and the improvement of existing sectoral models, and how adaptation will be modelled to include representation of critical triggers, time lags for implementation and effect, and constraints to effectiveness. All modelling groups within the task have developed initial Data Dictionaries and are iteratively updating their models for time-dependence and boundary conditions.
- The specification for the process-based modelling using the Soil and Water Integrated Model (SWIM) has been agreed. SWIM will be applied for a set of eight representative basins across Europe selected to span the range of climatic conditions across Europe and also to link to the regional case studies of WP3C (the Tay, Danube and Tagus catchments for the Scotland, Hungary and Iberia case studies, respectively).
- The specification of the new agent-based model (CRAFTY ABM) for Europe has been agreed. Progress has been made both on the development and application of the CRAFTY ABM. Work has focused on including and improving social networks between land manager agents and the representation of institutional agents (both of which are connected to the new institutional model that will be applied at the European scale). CRAFTY is running at the European scale and is currently being calibrated.

1. Introduction

The objective for the European Case Study (WP3B) is to advance and apply European scale methods and models to better quantify and understand impacts, risks, vulnerabilities and adaptation options associated with a range of scenarios for key economic, social and environmental sectors and their cross-sectoral interactions. This deliverable describes the specification for model improvement and development within the European Case Study of IMPRESSIONS to address this objective.

The research is ongoing, and while the general specification presented here has already been agreed, the implementation of the model improvements represents work in progress. As such, this report offers an early snapshot of the modelling activity within IMPRESSIONS' European Case Study.

1.1. Description of Work

According to the Description of work there are three main tasks relating to D3B.1:

Task 3B.1: Further development of a regional integrated assessment model for Europe

IMPRESSIONS will build upon the methodological advances for simulating cross-sectoral impacts, adaptation and vulnerability within the CLIMSAVE Integrated Assessment Platform (IAP). This task will further develop the IAP to simulate the response of complex multi-sectoral linked system(s) to multiple climate and non-climate pressures. The further development will be based on the scientific version of the IAP, not the stakeholder web-based version which includes the user interface, due to the need to automate the process of undertaking large multiple runs. The further development will include:

- Extending the modelling framework from the 2050s to 2100 to take account of long-term projections of climate and socio-economic change;
- Incorporating quantified model inputs from the IMPRESSIONS socio-economic scenarios (from WP2) and the European trade and migration boundary conditions from the global case study (from WP3A);
- Adding health impacts to the existing agriculture, forestry, water, biodiversity, coasts and urban sectors; and adding better representation of northern European tree species to the existing forestry modelling;
- Simulating dynamic time- and path-dependent impacts, adaptation and vulnerabilities. The method of improving time-, scenario- and capital-dependent adaptation processes will depend on the insights from Task 3.3 (see Deliverable D3.1), the ABM modelling (Task 3B.3) and Task 4.4 in WP4 on quantifying changes in coping and adaptive capacity.

Task 3B.2: Process-based impact modelling within Europe

This task will evaluate how any loss of information from using a simplified modelling approach (as in Task 3B.1) weighs against the gains in understanding of cross-sectoral interactions. A ecohydrological river basin scale model SWIM (Soil and Water Integrated Model) will be applied for a set of representative large river basins in different European regions to provide process-based modelling results at an intermediate scale between the continental and regional/local case studies described in WP3C. The SWIM modelling will link particularly closely with the Iberian regional/local case study which focuses on water resource and land use issues in two river basins, where SWIM will also be applied at a finer resolution. Application of SWIM for a set of representative river basins in Europe will enable more reliable simulation of high-end impacts and adaptation by better linking the regional and continental scales.

Task 3B.3: Construction of a new agent-based model for Europe

This task will develop a new agent-based model (ABM) for Europe which simulates institutional behaviour through time with respect to climate change. The modelling will be empirically-grounded using the institutional analysis being undertaken within the WP1. It will also take account of societal demand for ecosystem services and their supply by service providers (agents) within the context of the geographic variability of the five capitals (human, social, financial, manufactured and natural capital; linked with Task 4.4) and institutional interactions that describe the attributes of location. This task will be undertaken collaboratively with Task 5.3 in WP5 which will integrate the simulation of the firm-consumer nexus and their interactions with institutions into the ABM to produce outputs on socio-economic performance and economy-wide implications of the high-end scenarios.

1.2. Case Study Vision

The agreed Vision for the European case study, which this deliverable supports, is:

> *"The ambition of the European Case Study is to develop new knowledge and evidence on the impacts of, and adaptation to, high-end scenarios (HES) on key ecosystem service indicators across Europe. Simulated changes in a range of urban, health, agricultural, forestry, water and biodiversity indicators over time under high-end climate and socio-economic scenarios will be used to help stakeholders and decision-makers develop long-term adaptation strategies for coping with HES.*
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> *The case study will consider how impacts and adaptation responses in one 'sector' can have positive or negative effects in other sectors. The representation of adaptation decision-making in computer models will be improved to better understand how the effectiveness of adaptation under HES is influenced by timing and by socio-economic constraints. The insights gained through the stakeholder-led activities will provide capacity building for key decision-makers with respect to adaptive learning for coping with high-end scenarios".*

Within this case study vision, it has been agreed that the "decision-makers" represent the European Commission (and related institutions operating at the EU level) to make a clear distinction from the regional and national-scale of the decision-makers within the Regional Case Studies. As such, key European policies related to our decision-makers are the Water Framework Directive (WFD), Common Agricultural Policy (CAP); Habitats Directive; EU Forest Strategy; EU Floods Directive; Health 2020 and the EU Adaptation Strategy.

1.3. Links to other work packages (WP)

The specification for European model improvement and development links to other parts of the IMPRESSIONS project:

- **WP1** – empirical research interviewing the case studies' decision-makers to assess actual decision-making processes and information needs to ensure that scenarios, models and pathways are developed to: (i) meet the needs of decision-makers; and (ii) account for the actual (adaptation) decision-making patterns and behaviours of decision-makers;
- **WP2** - developing multi-scale, integrated climate and socio-economic scenarios, including high-end RCPs;
- **WP3A** – providing selected boundary conditions from the global scale RCPxSSP modelling (Figure 1.1);

- **WP4 and 5** – developing time-dependent adaptation-mitigation-transformation pathways that seek to achieve a stakeholder-identified vision; for which the European (rIAM; IAP; ABM) models will be used to a greater or lesser extent to model aspects of the transition pathways developed within the stakeholder workshops;
- **WP6A** – the European case study will have two workshops (WS#2 and WS#3 in the IMPRESSIONS workshop framework).

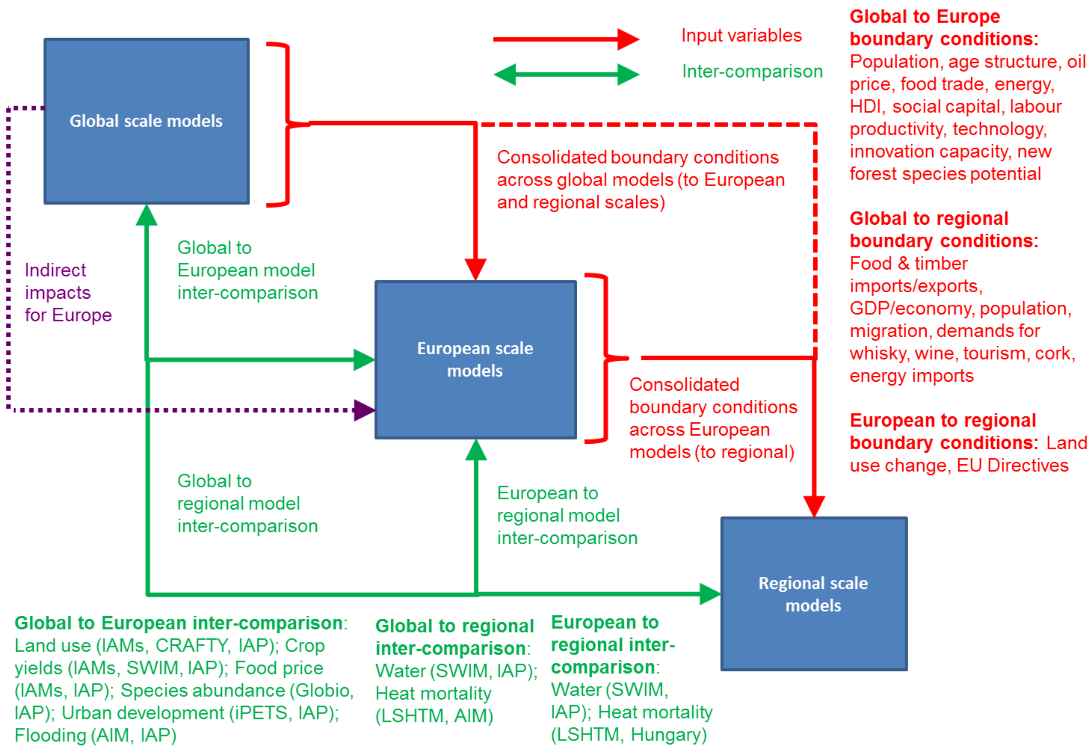


Figure 1.1: Potential cross-scale (Global-European-Regional) data transfers (presented at the Pisa modellers meeting, based on original model data dictionaries).

2. Specification of the regional Integrated Assessment Model (rIAM) for Europe

The regional integrated assessment model (rIAM) for Europe will be based on further development of the European version of the CLIMSAVE Integrated Assessment Platform (IAP) (Harrison et al., 2015 and papers therein; Cojocaru and Holman, 2012). The specification and model improvements for the new time-dependent rIAM have developed iteratively at and around the WP3 modellers meetings (held in London, Pisa and Cranfield). The following key elements of the specification and model development are described in this section:

- General specification and principles;
- Client- & Server-side software architecture;
- Scenarios and boundary conditions up to 2100;
- Meta-model specifications and improvements.

2.1. General specification

The following key technical points underline the specification of the rIAM:

- Computationally-efficient models (also known as meta-models or model emulators) will be used, given the longer runtimes associated with time-dependency simulations;
- All meta-models will be able to simulate decadal dynamic time- and path-dependent impacts and adaptation, and for at least one indicator to be able to be combined with coping capacity for vulnerability assessment;
- Model grid of 24,128 grid cells, based on the 10'x10' land grids of the Climatic Research Unit's (CRU) baseline climatology as used in CLIMSAVE, but expanded to include Malta and Croatia;
- Climate:
    - Baseline period of 1981-2010 (based on the WATCH-WFDEI data – http://www.eu-watch.org/data_availability);
    - Decadal climate periods of 2011-2020; 2021-2030 etc. until 2091-2100;
- Socio-economic :
    - Baseline year of 2010;
    - Decadal socio-economic variable quantification based on interpolation of the WP2 scenario products for 2010, 2040, 2070 and 2100;
- Five core scenario combinations (although system flexibility should allow each SSP to be combined with either RCP to explore uncertainty) as described in Deliverable D2.1 (Kok et al. 2015a):
    - SSP1/ We are the World + RCP4.5;
    - SSP4 / Riders on the Storm + RCP4.5;
    - SSP3 / Icarus + RCP4.5;
    - SSP3 / Icarus + RCP8.5;
    - SSP5 / Should I stay or Should I go + RCP8.5;
- To account for (some) climate model uncertainty, data from several climate models are to be included.

2.2. Client- & Server-side software architecture specifications

The technical construction of the rIAM is based on a web Client/Server architecture that will use both server-based and client-based computing solutions on the web. However, given the longer runtime associated with time-dependency (compared to the timeslice approach adopted within the CLIMSAVE IAP), the rIAM will disconnect the Client-side input and output sides of the software architecture to allow for long model runtimes on the server. There will therefore **not** be a real-time connection between the user, the meta-models and the graphical display of the model outputs.

The Client/Server architecture relies on three main computer programs: two on the Client computer (the *User Input Module* and the *User Output Module*) and one on the Server (the *Running Module*) (Figure 2.1). There will be three steps to the use of the rIAM:

1. The user selects the input data for the desired model run (such as the choice of climate scenario, source of global boundary conditions, etc.) on the User Input Module (Figure 2.2), which then sends the information to the server.

2. The Running Module on the server:
    a. processes the input data;
    b. runs the module chain of meta-models;

c. stores the output data in the database;
d. notifies the user by email of the model run's unique TicketID.

3. The user accesses the TicketID's model outputs from the database and views the results with the User Output Module.

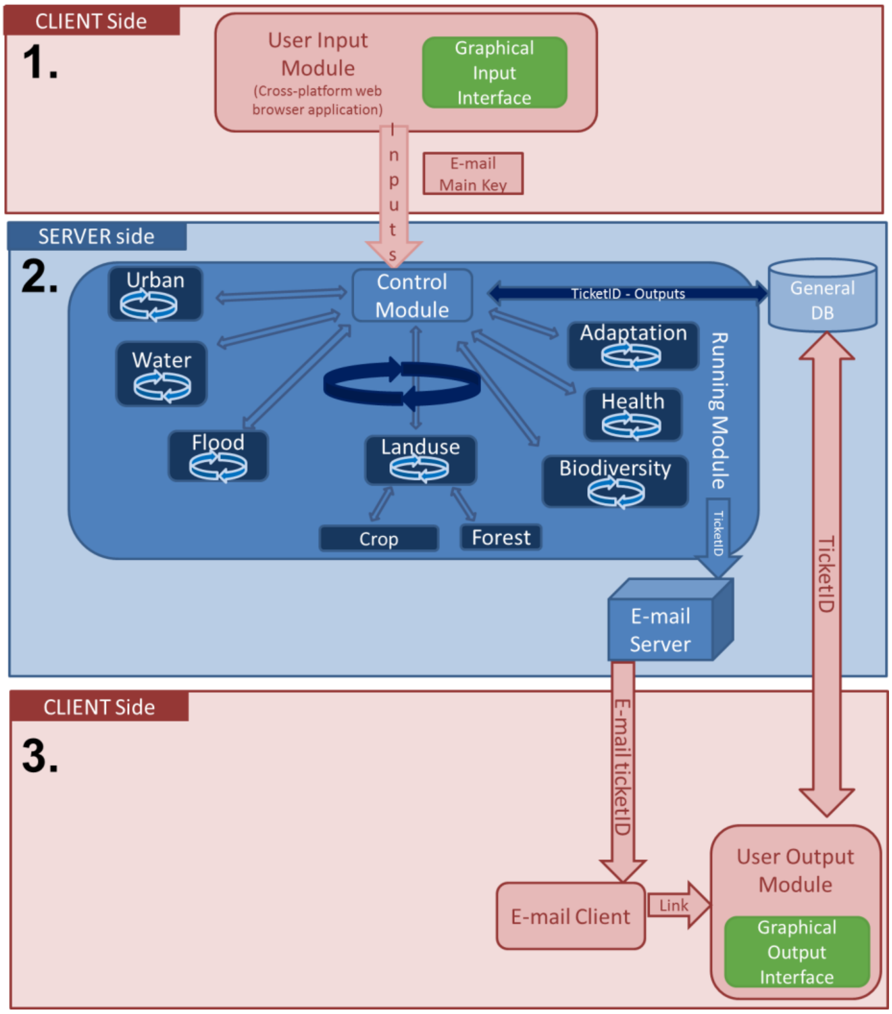


Figure 2.1: Schematic of the rIAMs software architecture.

The following components will reside on the Server computer:

- The main rIAM database which will organise the physical, climate, socio-economic and other temporary datasets required as inputs for the meta-models. It will be defined, organised and managed as a relational model database. The database structure is under development at the current time.

- The sectoral meta-models will be structured as Microsoft Dynamic-Link Libraries (DLL). Some of these DLLs may have their own databases to extract their internal data and some of them may also directly interact with other meta-model DLLs.

- A main Running Module based on ASP (Active Server Pages) / WebService technology which will collect queries from the User Input Module, analyse them, interrogate the rIAM main database for the required input data for the requested simulation, prepare the data for the meta-models, run the integrated flow of meta-models in an optimised way, store the output data in the database and send back the unique TicketID for that run back to the User.

It is also intended to use a solution that will be based on a batch input file (BIF) to enable the rIAM to be run in a batch mode. The BIF will be created outside the platform and will run on the server without using a graphical user interface.

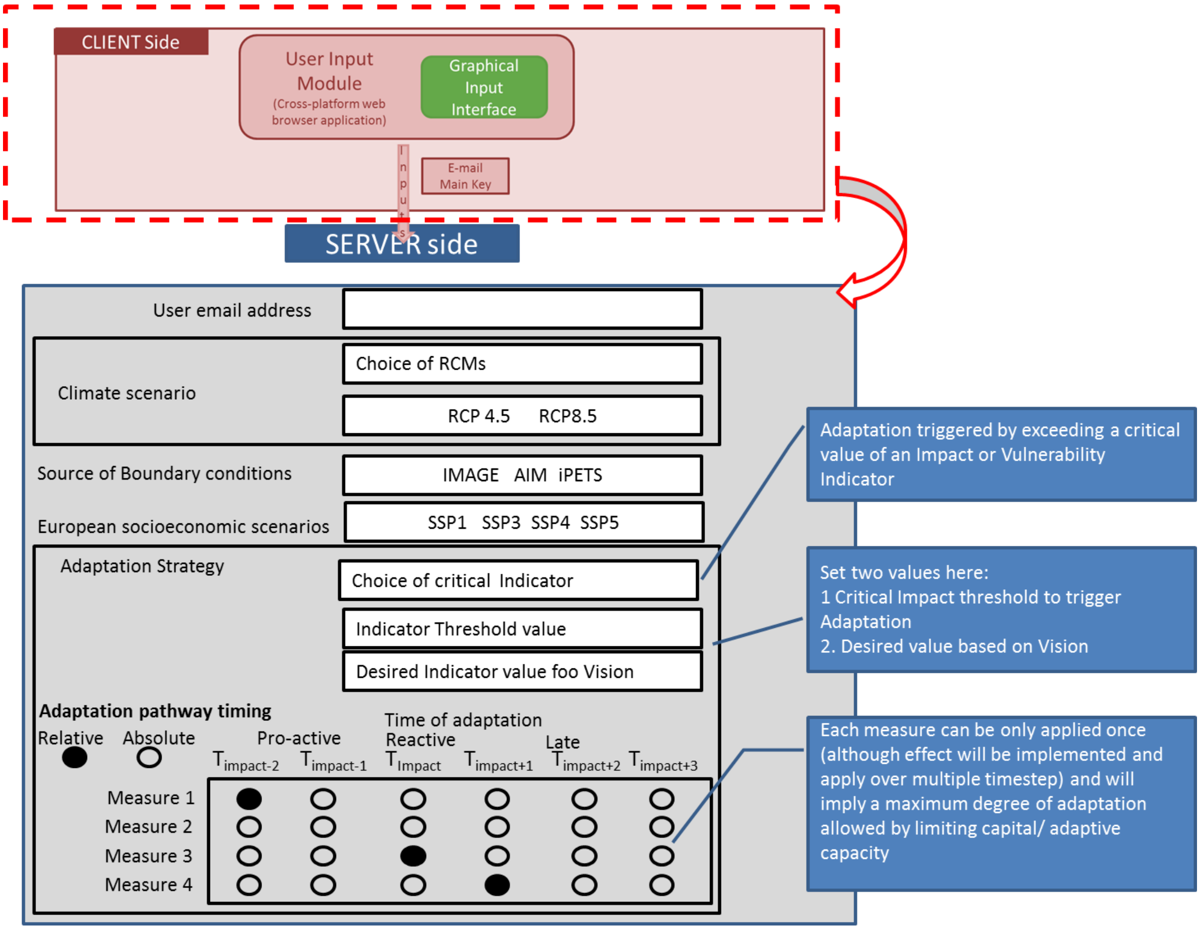


Figure 2.2: Initial prototype schematic of the client-side User Input Module, showing the selection of climate change scenario (RCM and RCP), source of boundary conditions (from a selection of global Integrated Assessment Models), European socio-economic scenario and the adaptation strategy.

2.3. Scenarios and boundary conditions up to 2100

2.3.1. Climate scenarios

The climate change scenarios within the rIAM will be based on climate model simulations that are available from CMIP5 and CORDEX for RCP8.5 and RCP4.5, given the focus in IMPRESSIONS on high-end climate change. Deliverables D2.1 (Kok et al. 2015a) and D3.1 (Carter et al., 2015) describe the process by which the limited number of climate model simulations which will be used as a core set within all IMPRESSIONS case studies were identified by WP2 and WP3, based on climate model sensitivity (reflecting lower, intermediate and high-end climate change) and the availability of regional model data. To account for (some) climate model uncertainty, data from several climate models are included. For RCP8.5, climate scenario data from four climate models are included that represent intermediate to high-end climate change and for RCP4.5, data from three climate models are used that represent low to intermediate climate change.

Kok et al. (2015a) thereby selected the following core set of climate scenarios:

- Representing high-end climate change:
  - RCP8.5 x HadGEM2-ES/RCA4
  - RCP8.5 x CanESM2/CanRCM4
  - RCP8.5 x IPSL-CM5A-MR/WRF;
- Representing intermediate climate change:
  - RCP8.5 x GFDL-ESM2M/RCA4
  - RCP4.5 x HadGEM2-ES/RCA4;
- Representing lower-end climate change:
  - RCP4.5 x GFDL-ESM2M/RCA4
  - RCP4.5 x MPI-ESM-LR/CCLM4.

2.3.2. Socio-economic scenarios

The socio-economic scenarios will be based on the Shared Socioeconomic Pathways (SSPs) in all case studies, but taking account of the CLIMSAVE scenarios (Kok et al. 2015b) within the European case study. Early in IMPRESSIONS, the decision was taken to limit the number of SSPs to be used in the participatory process to four (SSP1, SSP3, SSP4 and SSP5) for a variety of reasons explained in Deliverable D2.1 (Kok et al. 2015a). These four SSPs capture the low and high challenges to both mitigation and adaptation.

Deliverable D2.1 (Kok et al. 2015a) describes how the four CLIMSAVE socio-economic scenarios were matched with these four global SSPs and extended until 2100 (Table 2.1). For the European case study, it proved difficult to match SSP5 (Fossil-fuelled Development) with the CLIMSAVE scenarios, so this is being developed based on the global SSP storyline. However, SSP1 (Sustainability) and SSP3 (Regional Rivalry) matched well and SSP4 (Inequality) matched in part, so elements of both scenario sets are being combined. In the case of mismatches between the SSP and CLIMSAVE scenario narratives, it was decided that the global SSPs would take precedence.

Table 2.1: CLIMSAVE scenarios for Europe with illustrative examples for economic, environmental and social uncertainties, and most similar SSP (adapted from Deliverable D2.1; Kok et al. 2015a).

Scenario	Economic	Environmental	Social	SSP
We are the World	Gradual increase	Effective solutions	High social cohesion	SSP1
Icarus	Gradual decline	Ineffective solutions	Decline, then picking up	SSP3
Riders on the Storm	Rollercoaster downwards	Effective solutions	Low social cohesion	SSP4
Should I Stay or Should I go?	Rollercoaster up and down	Ineffective solutions	Low, but growing	No SSP equivalent

The socio-economic scenarios include both qualitative descriptions and quantifications. Qualitative descriptions include narratives and tables which summarise trends in key elements. These products will be developed using participatory approaches. Quantification of some key variables is provided by the SSP database v1.0 hosted by IIASA (https://secure.iiasa.ac.at/web-apps/ene/SspDb/). These can be directly used as model input and will be used as boundary conditions (see section 2.3.3.).

For quantification of other key model input variables, we use a combination of expert estimates directly derived using a 'Fuzzy Sets' based approach (carried out at the WP2 Wageningen workshop) and modeller expert judgment . This quantification process is ongoing between WP2 and WP3.

2.3.3. European Boundary conditions

The European boundary conditions will be provided from the IIASA SSP database and from selected outputs from simulations of the IMAGE global Integrated Assessment Model. These include:

- IIASA SSP database – population, age structure and GDP, by country;
- IMAGE outputs – gross value added (industry; services); thermal energy production (coal, oil nuclear); biomass energy; forestry demand; Human Development Index; price for agricultural products; technological change.

2.4. Specifications for meta-model integration

For efficient development of the time-dependent rIAM, each of the computationally-efficient models or meta-models is designed to be modular, independent and capable of replacement at any time. A specification for meta-model integration has therefore been developed to ensure successful linkage and integration of the models, irrespective of the final algorithms inside each of the models.

The development of the specification incorporates five distinct stages:

1. Defining the spatial resolution of the data to be transferred between meta-models:
    a. A resolution of 10' x 10' (10 minute by 10 minute), using the same grid as used in CLIMSAVE, based on the Climatic Research Unit's baseline climatology (CRU CL 2.1- Mitchell et al. 2003). This represents 24,128 land-based grid squares across the rIAM European case study.

2. Identifying and prioritising meta-models inputs and outputs (that are related to Impact, Adaptation and Vulnerability).

3. Identifying points of contact between the meta-models (Figure 2.3):
    a. Points of contact are the linkages and influences between sectors, and represent data transfers between the models. For example, the simulated area, location and type of urban development ("artificial surfaces" and "residential/non-residential development" from the urban model – RUG) affects the population exposed to flood risk ("People affected" as estimated by the Flood Model) and heat health impacts (as estimated by the Health model), river basin hydrological response ("Basin flow" from WaterGAP-H), the land available for agriculture and forestry ("land use allocation" from the land allocation model – SFarmMod) and consequently habitat availability (SPECIES biodiversity model).

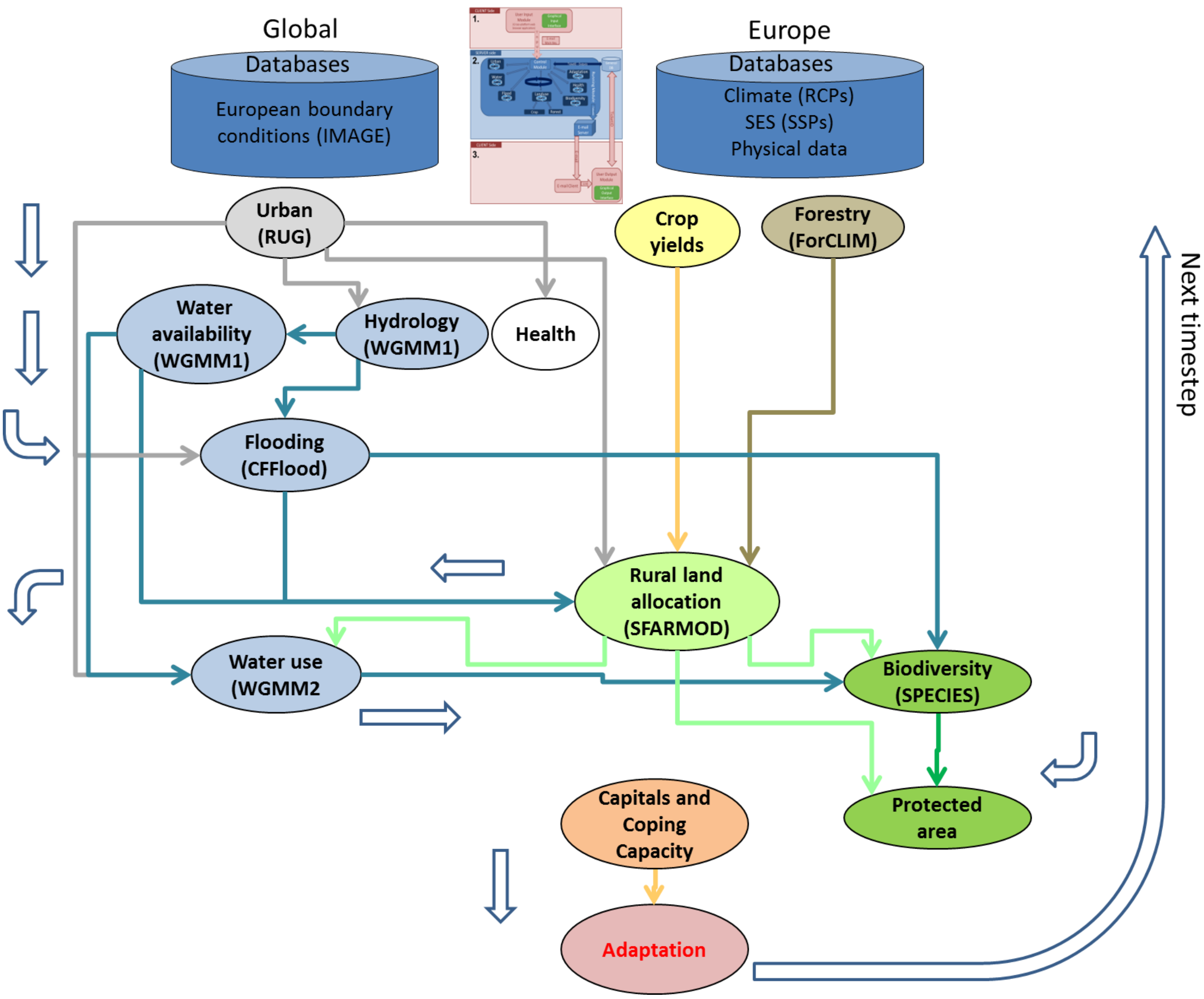


Figure 2.3: Simplified draft schematic of the linkages between the various meta-models (ovals) of the European rIAM

4. Specifying the data dictionaries for each meta-model;
   a. Within any single simulation of the rIAM, there will be six components of data reading and transfers:
      i. Data transfers from the user to the meta-models, representing the communication of input parameter values from the user to the models, via the User Input Module and the Running Module;
      ii. Data transfers between the meta-models, where the simulated output from one meta-model is an input to other meta-models;
      iii. Data transfers between the meta-models and the user, representing output variables that have been selected for storage and subsequent download by the user;
      iv. Data transfers from the rIAM database to the meta-models containing, for example, the input data for an SSP scenario;
      v. Data transfers via the rIAM Running Module of meta-model outputs from previous timesteps;
      vi. Data that is read into a meta-model from the meta-model's own internal dataset.

b. With the exception of (vi), all of the above represent transfers of data which need to be clearly defined in a transparent way. Data dictionaries therefore need to be developed for data associated with (i) – (v), which define for each variable or parameter:
   i. Whether it is an input to, or output from, the meta-model;
   ii. If it is a meta-model input, where it comes from – the rIAM database; the user via the User Input Module; another (named) meta-model; or meta-model outputs from a previous timestep.
      - For the latter (time-dependent case); in the timestep "n" a meta-model "x" (Mx) would need to use output data produced by the same (meta)model Mx in the previous timestep "n-1" or in a previous "n-i" (i<n) step(s). A variable name(s) needs to be allocated in the output part of the data dictionary (i.e. "out1_Mx", "out2_Mx", ...). In the input part of the data dictionary input variable name(s) also needs to be allocated specifying in the description of that variable the connection with the output variable from the previous step(s) (i.e. "in1_Mx" will contain the values of the variable "out1_Mx_current" produced by Mx in the step "n-i"). It will be the job of the master "Running" module to store "out1_Mx" data for each step "n-i" and to feed "in1_Mx" variable in the step "n" accordingly with the description from data dictionary.
   iii. Variable or parameter name as used by the meta-model's code, prefixed by the name of the model, e.g. RUG_PArtS_rdif is an output variable from the RUG model;
   iv. Long variable or parameter name, i.e. the conventional name given to the model parameter for example, RUG_PArtS_rdif is the 'Relative change in artificial surfaces';
   v. Definition of parameter or variable – providing an unambiguous 'plain English' explanation, for example RUG_PArtS_rdif is the 'Percentage difference in artificial surfaces relative to the baseline value';
   vi. Dimensions - Single; Integer8, 16, or 32;
   vii. Units;
   viii. Spatial unit - whether the data is provided for each grid cell, polygon, river basin, cluster, NUTS2, country, or a global value;
   ix. Number of values per spatial unit, which allows for, for example, multiple soil types within a single grid cell;
   x. For outputs, what is the destination of the variable within the rIAM - whether it to be used by another meta-model(s) and/or displayed in the User Output Module.

5. Standardising the data dictionaries across all of the meta-models:
   a. The final step in the process is the standardisation of the data dictionaries across all of the meta-models, so that each end (rIAM, database or meta-model) of a data transfer (for example, meta-model to meta-model; or rIAM to meta-model) uses the same data dictionary. This then allows the data transfers in terms of model variables and parameters to be defined and implemented.

All of the meta-models themselves will be implemented as Microsoft Dynamic-Link Libraries (DLL), but which can be developed in various software languages: such as Microsoft C++, Microsoft C#, Microsoft VB, Delphi, etc. as both managed and unmanaged code. They will be embedded in the main Running module, working as one piece of software. The Running module will feed the DLLs with data, run the DLLs and collect and store the outputs. The exchange of data will be made available based on structures of data transferred by pointers to minimise the time required for data exchange. In this approach, the meta-model is told where to point data within the internal memory, rather than the data being physically transferred to the model, with consequent time savings given the number of grid cells (>23,000).

3. Description of planned meta-model improvements

A number of the models within the rIAM are based on the meta-models used within the CLIMSAVE IAP and described in Holman and Harrison (2012) and within the CLIMSAVE Special Issue (Harrison et al. 2015). In order to ensure that decision-maker relevance is taken account in the model development, the current model indicators have been mapped with WP1 against the identified high-level objectives for the identified EU policies or strategies in Section 1.2 (Table 3.1). In this context, the following sections therefore focus on the improvements of these existing models (for time-dependency and/or for high-end scenarios) and on the description of the new models (health, forest).

3.1. Urban

The urban model used in the rIAM will represent further development of the RUG meta-model used in the CLIMSAVE IAP. The RUG meta-model was based on a look-up table of artificial surface extent that was populated by multiple scenario runs of the RUG model. RUG simulates the change in artificial surfaces for each NUTS2 region as a function of changes in the population (total) and GDP (per capita), assuming a fixed ratio of residential to non-residential urban areas. This function was calibrated from historical observational data across Europe.

Changes in the extent of artificial surfaces at the NUTS2 level are allocated to the 10' CLIMSAVE grid based on: (a) the preference of society to live in urban areas versus the countryside; (b) the preference of society to live at the coast; and (c) the strictness of spatial planning (compact versus sprawling development). The modelling of these preferences and spatial allocation of urban change was initially undertaken at a fine spatial resolution (1km^2) before being aggregated to the CLIMSAVE 10' grid within the look-up tables.

3.1.1. Changes to RUG within the rIAM

The CLIMSAVE RUG model and meta-model (described above) will be changed substantially as part of the IMPRESSIONS rIAM. A number of improvements have been envisaged and are being implemented to ensure RUG is more suited to the needs of the IMPRESSIONS project.

1. Higher thematic detail
RUG will be updated to integrate further with population structure (age-group) data available at the NUTS2 level (as published by Eurostat). The integration of population projections (from the IIASA SSP database) and population structure (Eurostat), by an associated population model, will allow the reporting of projected changes in age-group structure at the NUTS2 level under different SSPs. It has been demonstrated that societal preferences for different residential types, and their location, is a consequence of life-cycle stage or age-group (Fontaine & Rounsevell, 2009; Fontaine *et al*, 2014). Consequently, predicted changes in population structure at the NUTS2 scale will influence the demand and societal preferences for different artificial surfaces. For example, a young-working population may prefer high density urban centres while older populations have a greater preference for coastal locations and/or suburban housing. Age-group preferences, and their influence on artificial surface expansion, will be modelled at both the NUTS2 and 10' scale.

Table 3.1: Draft mapping of preliminary model outputs to high-level policy objectives.

	WFD				Habitats Directive			CAP			Forest Strategy			Floods Directive					Health 2020		
	Good Ecological status	Securing drinking water supplies	Reduced emissions of hazardous substances	Protection of terrestrial & marine waters	Restoration of natural habitats and wild species.	Protection for animal & plant species	Special areas for conservation	Viable food production	Management of natural resources	Balanced territorial development	Satisfy demand for raw materials	Sustainable forest management	Multi-functional role of forests and forestry	Reduce impacts on human health	Reduce impacts on the environment	Reduce impacts on cultural heritage	Reduce impacts on the economy	Reduce impacts on infrastructure	Improving health for all	Reducing health inequalities	Leadership and governance
Urban extent / type	x																x	x			
Population density & age-structure																			x	x	
Biodiversity index				x	x	x	x		x			x	x		x				(x)		
Land use diversity				(x)	x	x	x		x		x	x	x		x	x			(x)		
Food prod. Per capita								x													
Total cropped area									x	x					x	x					
Area of risk of flooding									x	x			x	x	x	x	x	x			
People flooded in 1/100 y event												x	x	x						x	
Coastal habitat change				x			x										x	x			
Pesticide usage	x		x						x			x	x	x	x						
Fertiliser usage	x		x						x				x	x	x						
Total water use	x	x		x																	
Falkenmark index		x						x		(x)											
Water exploitation index	x	x						x	x								x				
Irrigation usage	x							x							x		x	x			
Unmanaged land					x	x				x											
Intensively/extensively farmed					x	x	x	x	x	x		x			x		x				
Areas of habitats				(x)	x	x	x		x			x	x		x		x				
Species specific climate and habitat suitability					x	x			x	x			x								
Potential wood yield											x	x					x				
Forest area				x	x	x	x				x	x	x		x						
Potential net primary production				x			x			x	x	x					x				
Potential carbon stock									x			x	x		x		x				
Agricultural yields								x	x	x											
Protected Areas					x	x	x														
Health mortality																			x	x	

To support the inclusion of population structure and age-group driven preferences, the model will consider, and independently model, three residential types: (a) high density urban centres; (b) intermediate density urban clusters (towns, suburban areas); and (c) low density rural areas. The definition and baseline delineation of these urban types will be based on the Eurostat 'Degree of Urbanisation' dataset. These residential urban types will be accompanied by a fourth class; non-residential (manufacturing and industrial).

2. Population density as a driver for urban sprawl

Residential urban demand will be modelled, at the NUTS 2 scale, as a function of: (a) the total population; (b) population structure (age-group/life-cycle stage); (c) the known correlation between life-cycle stages and their preference for each residential type; and (d) population density. Within this framework, for a given scenario, the population structure will drive the demand for each residential type and the model will predict the required extent of each residential type.

Population density allows a link to be established between the population and required urban extent. Population density can be modified, from current estimates, to reflect scenario (SSPs) storylines or predicted planning policies. For example, if societal preferences change towards high-rise living in compact, minimal footprint urban areas, this can be reflected by increases in the population density.

3. Spatially allocating urban changes to the 10' cells: Societal preferences

The predicted NUTS2 scale changes in the extent of each residential/non-residential artificial surface type will be spatially allocated to the 10' cells of the IMPRESSIONS grid on the basis of a series of spatial allocation rules which describe: (a) the preference of society to reside in urban areas versus the countryside/regions with increased greenspace; and (b) the preference of society to reside at the coast, or near natural features such as waterbodies (lakes, rivers) and protected areas. These preferences will be accompanied by an additional term which describes the spatial autocorrelation of each artificial surface type. This spatial correlation term reflects the tendency of artificial surface expansion to be influenced by surrounding land use types. For example, high density urban centres will predominantly be developed in close proximity to existing centres or intermediate density suburbs. They are unlikely to occur in countryside areas.

Restrictions, applied at the 10' cell, will ensure that there is no further expansion of urban areas within protected areas, and no expansion into impractical building areas (waterbodies, regions with steep slopes, etc.).

4. Model resolution

The rIAM RUG meta-model will be implemented at the native (10' x 10') resolution of the reporting grid which will enable run-time implementation and dynamic modelling, as opposed to the predefined set of look-up table parameters of the CLIMSAVE RUG model. Within the time-step dependent meta-model, the results from preceding time-steps, across the full rIAM, will form the basis of the RUG implementation at the subsequent time-step. Consequently, artificial surface expansion will build from the fabric of the preceding time-step taking account of increased/decreased protected areas.

5. Output variables

The previously described RUG updates will significantly improve the thematic detail at which the model outputs are reported. Outputs will now describe, per 10' cell, the extent of four artificial surface types (high, intermediate, low density residential and non-residential), total population and the breakdown of this population into broad life-cycle stages.

3.1.2. Policy relevance of RUG within the rIAM

Updates to the RUG model and meta-model will allow policy questions to be answered relating to different outcomes for urban development. These urban outcomes will have different environmental impacts, which are assessed throughout the rest of the rIAM, including flood damage, biodiversity, rural land use and health. The input parameters which can be modified in an adaptation experiment to test these outcomes include changes in: (a) planning (population density) and the resulting sprawling/compact urban developments; (b) the preferences of individuals to live in urban centres, suburbs or rural areas; and (c) education/awareness raising about societal location choices, for example, to support increases in building heights to limit urban expansion, and potentially planning urban green space.

3.2. Health

3.2.1. Description of the health model

The health model that will be included within the rIAM will model the impacts of heat on the population. The heat-health model is a new model being developed for the IMPRESSIONS project and, therefore, does not benefit from an established framework under the CLIMSAVE platform. The model will quantify heat-related mortality under assumptions of climate change, population growth and ageing, and urban change. The spatial model is applied to the 10x10 minute grid. It is time dependent, requiring 10 year inputs and providing outputs for annualised heat-related mortality attributable to climate change, by age group and by sub-region, based on a counterfactual of no warming across Europe. Heat-related mortality will be quantified for the following three age-groups: 0-64, 65-74, 75+ as risk increases greatly with age. Future baseline mortality will be estimated based on the all-cause mortality projections that have been produced for the SSPs (Lutz et al. 2014[1]). The model will use inputs of population from the RUG model (see section 3.1) linked to urban migration flows, which will be used to estimate future age-specific mortality. Population attributable mortality will be based on the method used by Vardoulakis et al. (2014).

New exposure response functions are being developed based on the model developed by Gasperrini et al. (2010). These functions better characterise the population response at the extreme end of the (exposure) temperature distribution, in order to capture the uncertainty in assessing impacts under high-end scenarios.

We will explore linking the model to the RUG model within the overall rIAM framework. The RUG model will provide indicators of dense urban areas which will affect local temperature exposures (based on current observations) [see Kershaw et al. 2010].

3.2.1. Policy relevance of the health model within the rIAM

The new health model will allow an exploration of how future change, manifest through changing climate, urbanisation, population numbers and age-structure, will affect heat-related health impacts in Europe. The model will enable the effectiveness of alternative adaptation scenarios for acclimatization (behavioural, physiological, etc.), linked to the European SSP narratives, to be explored.

[1] Data available at http://witt.null2.net/shiny/wittgensteincentredataexplorer/

3.3. Water availability and use

The WGMM (WaterGAP meta-model) of Wimmer et al. (2015) that was used within the CLIMSAVE IAP will be modified for use in the IMPRESSIONS rIAM. The WGMM emulates the performance of the WaterGAP3 model (Alcamo et al. 2003; Döll et al. 2003; Verzano 2009; Flörke et al. 2013) for hydrology and water use. To reduce model runtime and input data requirements, the spatial resolution of WaterGAP3 (5 x 5 arc minute) is aggregated to around 95 European river basins greater than 10,000 km². Each river basin represents either a large natural river catchment or a cluster of several smaller catchments with similar hydro-geographic conditions. The meta-model calculates annual mean values.

3.3.1. Changes to WGMM within the rIAM

1. Water availability

The meta-model representation of the WaterGAP model is realised by creating Impact Response Surfaces (IRS) tailored to river basins relating changes in mean annual water availability (*WA*) to simultaneous changes in temperature and precipitation. Response surfaces are derived from the output of WaterGAP3 simulations of water availability (30-year average) with systematically modified baseline climate inputs. The high-end focus of IMPRESSIONS requires that the IRS's developed in CLIMSAVE are expanded to include the greater range of changes (especially for temperature) associated with RCP8.5 out to 2100.

As a consequence change factors capturing the projected future changes in temperature ([0, 0.5,..., 11°C]) and precipitation ([-60, -55,..., +40%]) will be applied to spatio-temporal patterns in the climate dataset for the baseline period 1981-2010 (WATCH WFDEI, see Weedon et al. 2014). When the meta-model is run with specific climate scenario input of gridded mean annual precipitation and air temperature, the change in temperature and precipitation in each river basin compared to the baseline is computed and used to derive the scenario value for *WA* from these response surfaces.

2. Water use

The calculation of water withdrawals (*WW*) and consumption (*WC*) at the river basin level in the domestic, manufacturing and electricity sectors is based on WaterGAP3 results for the year 2010 (cmp. Flörke et al. 2013). Relative changes in *WW* and *WC* are proportional to changes in the following drivers at the country level: population, gross domestic product, manufacturing gross value added, thermal electricity production and water savings due to behavioral and technological change. These meta-model inputs will be derived from the IIASA SSP database, the European boundary conditions and the quantification of the European SSPs, as previously described.

Modelling of agricultural water use is based on the coupling of WGMM and SFARMOD via irrigation water supply and usage. WGMM computes an estimate of water availability and water demand in the non-agricultural sectors based on climate inputs and socio-economic drivers, respectively. These estimates are used to derive the maximum volume of water available for agriculture in each river basin. SFARMOD calculates the actual use of irrigation water within individual grid cells under the constraint that water available for irrigation must not be exceeded in a river basin. The actual volume of irrigation water used in the river basin is passed back to WGMM.

3. Time-dependency

The basic assumption in the hydrology part of WGMM is that the input (gridded values) of annual precipitation and mean temperature are representative for a period of time that is long enough to ensure that water storage terms in a basin (soil moisture, groundwater) reach a steady state according to the climate conditions in this period. With time steps representative for a period of ten years it can be assumed that this assumption is valid. Hence, the meta-model approach as developed for the CLIMSAVE project is applicable for modelling time-dependency driven by 10-year-average values of precipitation and temperature. In the water use part, modelled values can be interpreted as representative for a specific year as there are no storage terms that need to reach a new steady state. Therefore, the approach is suitable to model annual time series and can be applied also to 10-year time steps.

3.3.1. Policy relevance of WGMM within the rIAM

Table 3.2 shows the input parameters of the WaterGAP meta-model. The most relevant adaptation responses that can be investigated by the WGMM through modification of input variables are: (a) water savings due to behavioral change; (b) water savings due to technological improvements; and (c) water demand prioritisation, i.e. the distribution of water resources to different sectors. Table 3.3 lists the key policy-relevant model outputs indicating the EU policies informed.

Table 3.2: Input parameters of the WGMM.

Input parameter	Spatial scale	Source
Annual precipitation	10 arc-minute	WP2
Mean annual temperature	10 arc-minute	WP2
Population	Country	Global IAMs / SSPs
Gross domestic product	Country	Global IAMs / SSPs
Gross value added (manufacturing)	Country	Global IAMs / SSPs
Thermal electricity production	Country	Global IAMs / SSPs
Water savings due to behavioural change	Country	Global IAMs / SSPs
Water savings due to technological improvements	Country	Global IAMs / SSPs
Irrigation water use	River basin	SFARMOD (rIAM)

Table 3.3: Output parameters of the WGMM.

Output parameter	Description	Spatial scale	Relevant for EU policy
Water exploitation index	Withdrawal-to-availability ratio	River basin	WFD
Falkenmark Index	Water availability per capita	River basin	
Sectoral/total water use	Water withdrawals by sector or sum of sectoral withdrawals	River basin	WFD

3.4. Flooding and wetland habitats

The CFFlood meta0-model (Mokrech et al. 2015a, b) will be further developed in IMPRESSIONS (Figure 3.1). It is a 2-dimensional simplified process-based model that simulates: (a) coastal flood impacts; (b) fluvial flood impacts; and (c) wetland change/loss due to future climate and socio-economic conditions. A range of adaptation options that are designed to reduce impacts to acceptable levels will be implemented in the model based on impact thresholds. The model outputs will be communicated to the user interface as well as to other sectoral meta-models within the rIAM.

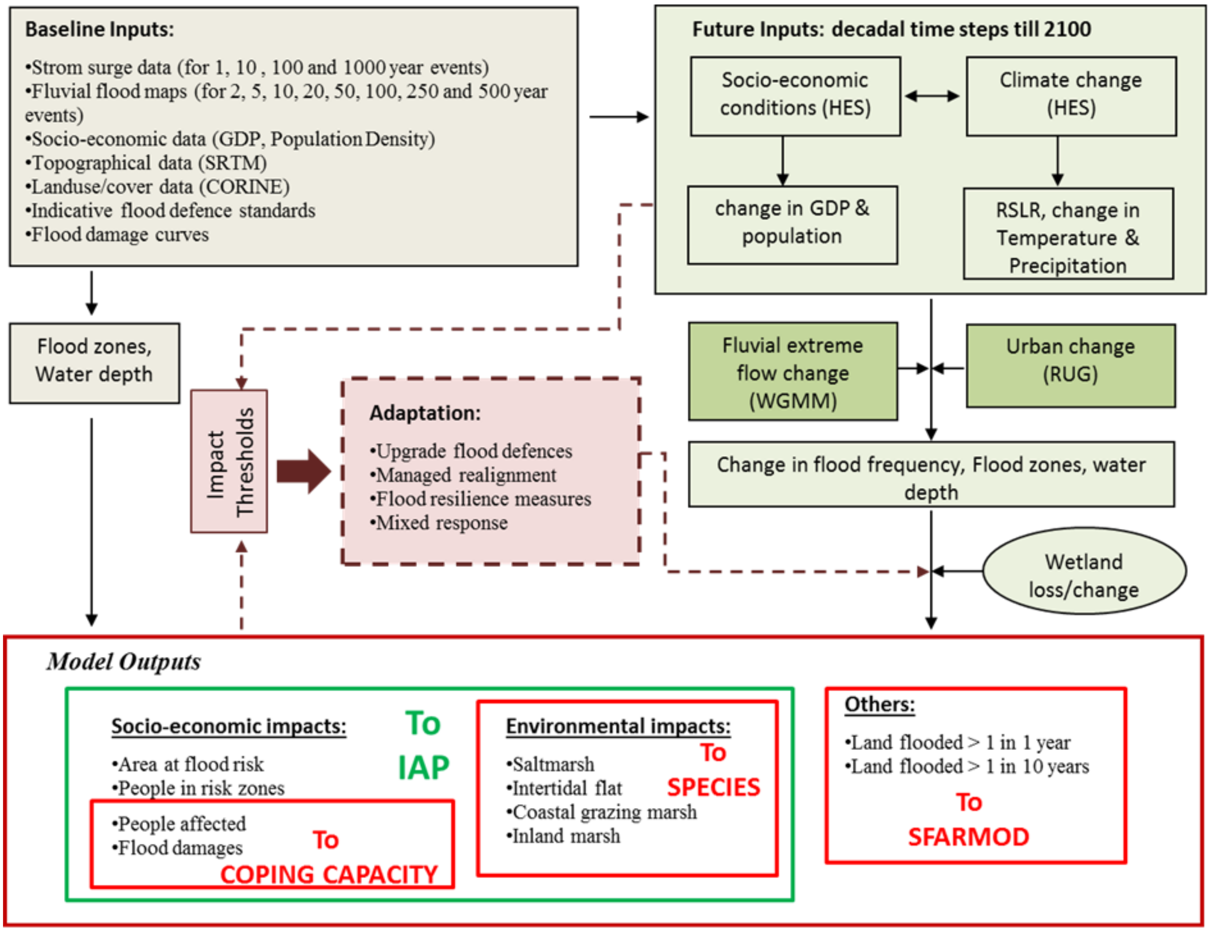


Figure 3.1: Overview of inputs, adaptation measures and outputs of the CFFLOOD meta-model. GDP: Gross Domestic Product, RSLR: Relative Sea-Level Rise.

3.4.1. Changes to CFFlood within the rIAM

1. Input data

The CFFlood model uses European and global datasets as described in Mokrech et al. (2015). Some of these datasets will be upgraded to newer versions to represent the 2010 baseline year in rIAM. For example the CORINE land cover 2006 version 17 with some gaps filled from earlier versions will be used to represent land cover classes and be used to update the indicative flood protection data for Europe following the methodology implemented by Mokrech et al. (2015).

2. Time-dependency in the CFFlood model without adaptation

The CFFlood model as described in Mokrech et al. (2015) will be re-designed to simulate impacts and vulnerability at decadal time steps up to 2100 in a dynamic approach without changes in flood protection and management policies over time. The flood impacts are simulated for selected events that are influenced by the flood protection level at the baseline year as well as by the progressive increase/change of climate and socio-economic pressures during the 21st century. Thus, the inputs to the model at a time step (e.g. 2070) will be the data inputs at the baseline year and the changes in climate pressures (i.e. sea-level rise and precipitation) and socio-economic (i.e. GDP and population) conditions from the baseline year. The effects of sea-level rise and the change in GDP are directly simulated in the flood model, while the effects of changes in precipitation and population are provided through the WGMM (section 3.3) and RUG (section 3.1) models (Figure 3.2). The effects of change in climate pressures on wetland habitats are simulated at decadal time steps starting from the 2010 baseline year (Figure 3.3). At each investigated time step the CFFlood model uses the simulated habitats from the previous investigated time step.

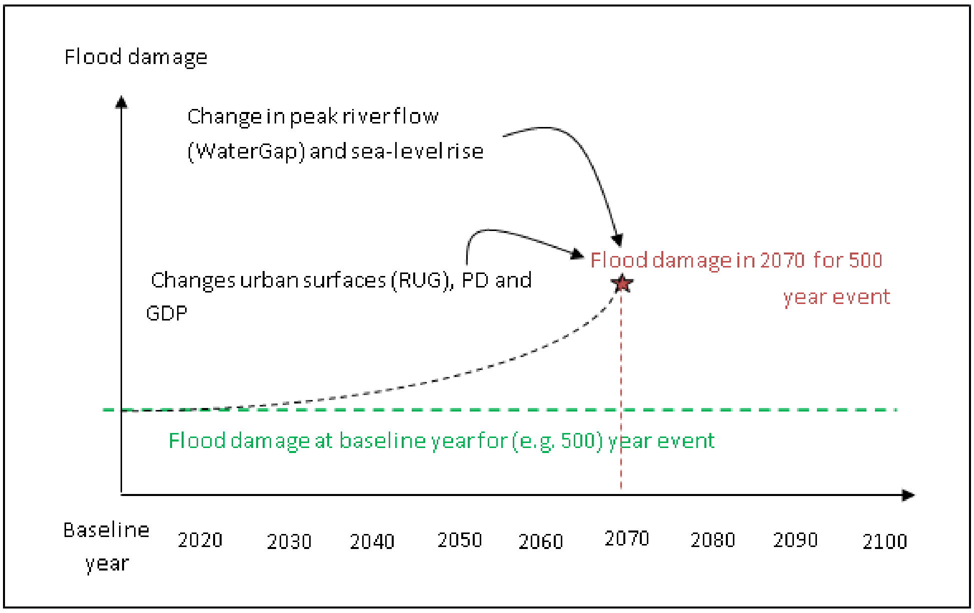


Figure 3.2: Flood damage in 2070 for a specific flood event (e.g. 1 in 500 year event) simulated based on changes in climate and socio-economic pressures – the black dashed line represents a potential trend in flood damage.

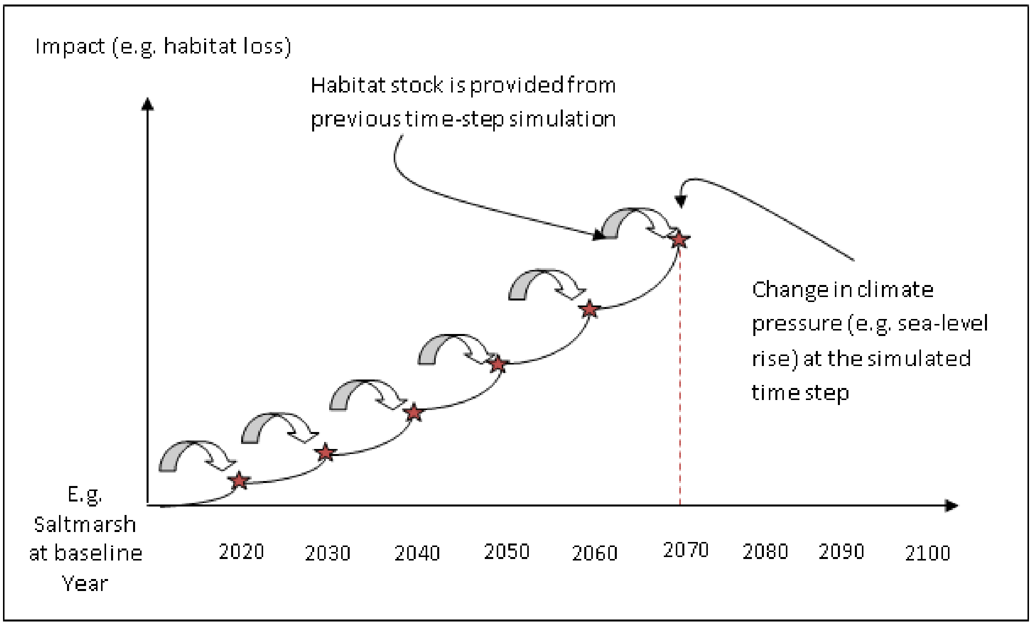


Figure 3.3: Habitat loss (e.g. saltmarsh) simulation in (e.g. 2070) using the time-dependent approach – each time-step simulation (i.e. ★) uses a habitat simulation from previous time-step and climate pressures (e.g. sea-level rise) at the simulated time step.

3. Time-dependency in the CFFlood model with adaptation

A suite of adaptation measures that are designed to reduce impacts, are to be integrated and implemented in a dynamic way within the CFFlood model. These measures include upgrading flood protection by different levels, realignment of flood defences to create accommodation space for habitat creation, and introducing resilience measures to urban properties. One to two decade time spans are considered sufficient for planning and implementing these adaptation measures. For example, raising a dike to increase flood protection by 50% can be planned and completed in 10 years while significant upgrades of flood protection systems (e.g. increase by 1000%) may require the development of more sophisticated structures (e.g. flood barriers), which may require 10-20 years for planning and construction.

Two economic and environmental impact indicators (i.e. flood damage and saltmarsh loss) are proposed as triggers for implementing relevant adaptation measures in a pro-active manner to avoid critical threshold values following adaptation pathways. Figure 3.4 shows a schematic representation of an impact indicator (e.g. flood damage) and the implementation of adaptation at time steps. For example, the flood damage may reach a critical threshold in 2050, which will trigger the need to implement adaptation. Thus, an adaptation measure will be assumed to start in 2040 and it will become effective in 2050. The sharp decline in impact in 2050 is an indication that the selected adaptation measure is completed and effective. However, temporary measures during the adaptation implementation may lead to gradual effectiveness as indicated by the dashed brown curve 1 for one-decade implementation time span and as indicated by the dashed brown curve 2 in the case of two-decade implementation time span. Thus, the impact in 2050 will be reduced to a specific level (e.g. baseline year level, above or below baseline year level). The model will then investigate the impact in 2060 and repeat the same described process again (if needed) till 2100.

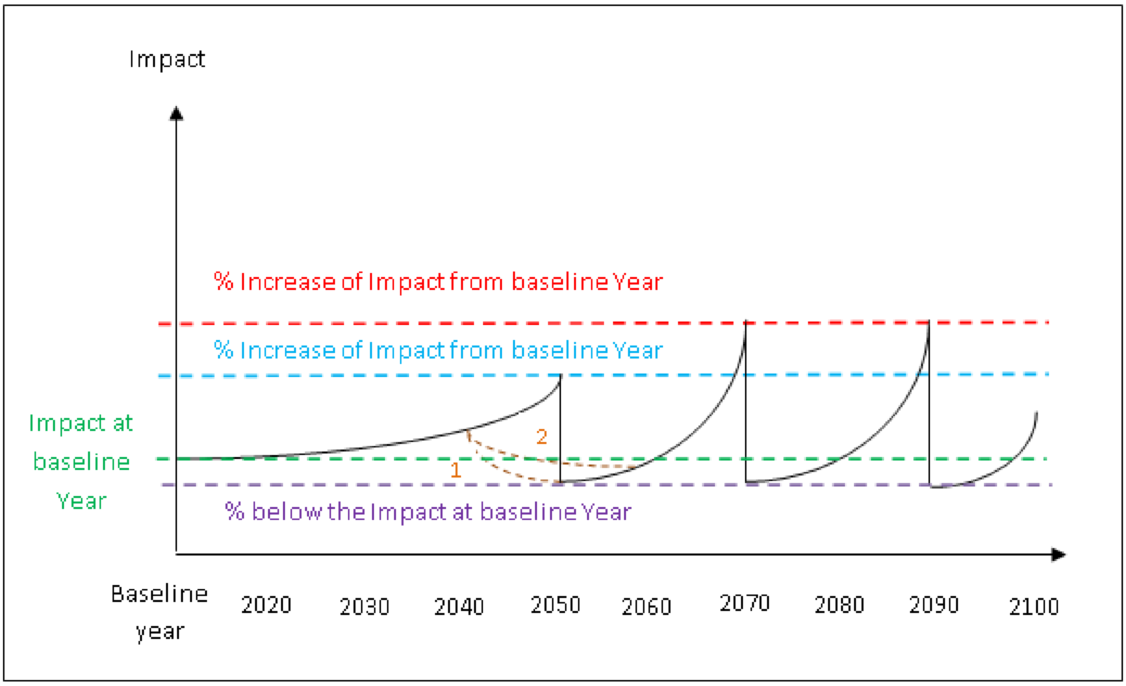


Figure 3.4: Schematic representation of the implementation of adaptation measures that are designed to reduce impacts of climate and socio-economic pressures to acceptable levels below thresholds. The dashed brown curves (1 and 2) are examples that indicate the existence of temporary measures for reducing impacts while the implementation of the selected adaptation measure is underway.

3.4.1. Policy relevance of CFFlood within the rIAM

The outputs of the CFFlood model related to flood impacts in urban and rural environments and to changes in coastal habitats have relevance for a number of the identified policies. These include the Flood Directive (impacts on the environment, human health, economy and infrastructure); the

Habitats Directive (particularly on coastal protected areas); CAP (through flooding impacts leading to agricultural land use changes and resultant impacts on food production). The model will allow a range of alternative behavioural and structural responses to flooding to be explored.

3.5. Forestry

Similar to the health model, a new forestry meta-model is being implemented in the rIAM to better represent northern tree species and the potential for changes in species selection as a consequence of high-end scenarios. This section describes the detailed process-based model (ForCLIM) which will be used to develop the meta-model and the anticipated meta-modeling approach, as well as inputs, outputs and adaptation options within the forest meta-model.

3.5.1. Description of ForClim

ForClim is a cohort-based dynamic vegetation model that was developed to analyse successional pathways of various forest types in Central Europe (Bugmann 1996) and other parts of the temperate zone[2] (Bugmann and Solomon 1995, Bugmann and Solomon 2000, Shao et al. 2001). Based on the theory of patch dynamics (Watt 1947), tree development (growth), establishment and mortality are simulated with an annual time step on small areas ("patches", see Figure 3.5); while the influence of climate and ecological processes is taken into consideration using a minimum of ecological assumptions. No interaction is assumed between trees of adjacent patches, i.e. the successional pattern at larger scales (forest stand to landscape) is obtained by averaging the simulation results from many patches (Bugmann 2001).

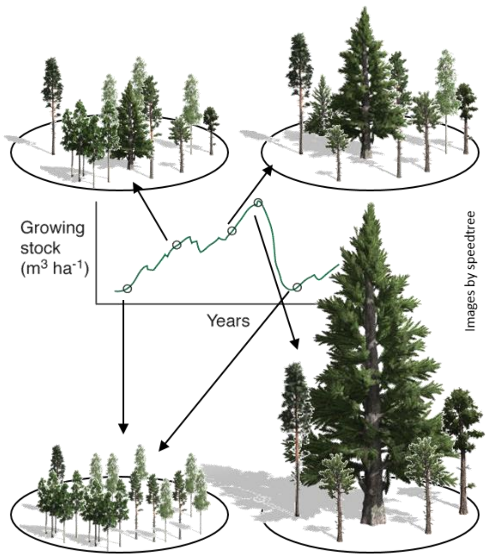


Figure 3.5: Schematic of the gap model ForClim.

ForClim is designed as a modular model, i.e. it is composed of four independent sub-models, which are assembled through defined interfaces (state variables) to form a complete forest gap model as described in Figure3.6. The four sub-models are:

- The WEATHER sub-model provides time-dependent weather data (using a weather generator) that is then used to calculate bioclimatic variables required by the PLANT sub-model;

[2] Ongoing model improvements at ETH-Z aim to further increase the reliability of its predictions for extreme climatic conditions, such as under extreme scenarios of climate change.

- The WATER sub-model uses the bioclimatic variables and limited site-specific parameters (e.g. soil water holding capacity = "bucket size") to compute an annual site-specific drought index based on a modified version of the soil water balance model by Thornthwaite and Mather (1957) (Bugmann and Cramer 1998).
- The PLANT sub-model calculates establishment, growth, and mortality of trees on the forest patch, based on the bioclimatic input variables from WEATHER and WATER:
    - Saplings are established in the patch with a predefined diameter at breast height (dbh) of 1.27 cm, provided that a range of biotic and abiotic factors are within species-specific thresholds (Bugmann 1996);
    - Radial tree growth is modelled for the patch based on the carbon budget by Moore (1989), with several modifications (Rasche et al. 2012): a species-specific optimal growth rate was adjusted based on environmental factors (light, plant-available nitrogen, degree-day sum, soil moisture) and crown length. The resulting volume growth was allocated dynamically to height and diameter growth based on available light and the species' shade tolerance;
    - Tree mortality is triggered - at the individual tree scale - by both a constant species-specific and age-related mortality probability and a stress-induced mortality, which is activated in case of slow growth (happening for two consecutive years).
- The MANAGEMENT sub-model can simulate several cutting/harvesting and thinning techniques (Rasche et al. 2011; Figure 3.6) defined by the type (e.g. clear cutting, 'plentering'), frequency and intensity of management operations.

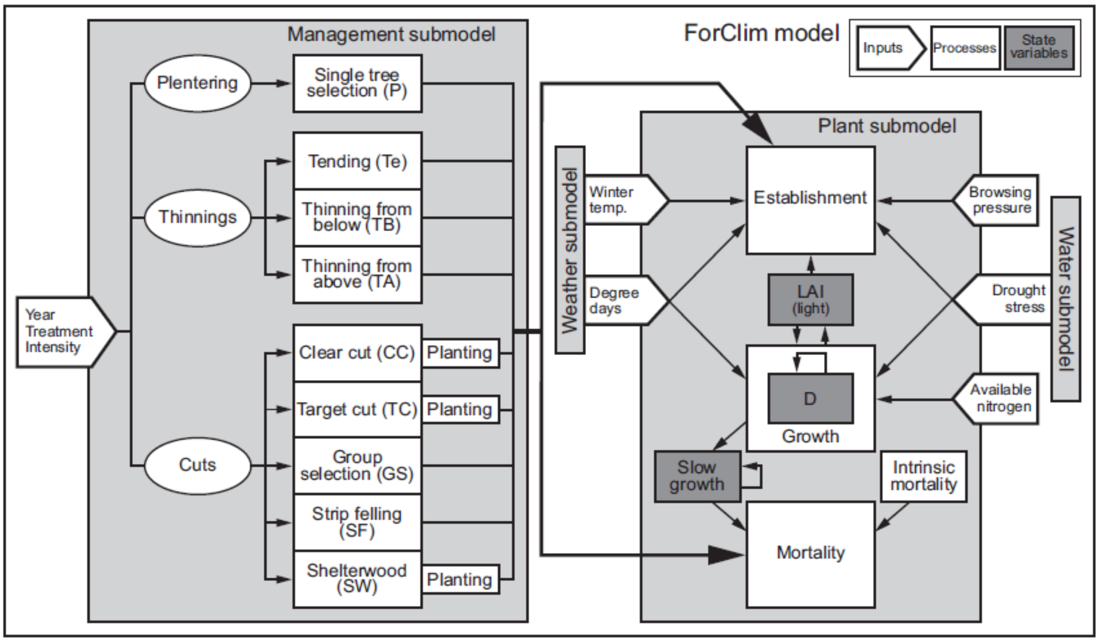


Figure 3.6: Structure of the ForClim model with sub-models management, plant, weather and water (Rasche et al. 2011).

1. *Meta-modelling approach*

The approach currently considered to develop a meta-model of ForClim is to use multiple regression techniques to predict the main outputs (e.g. expected timber yield) based on climatic conditions (current and future), tree species, forest state and management.

2. *Main relevant inputs*

The main relevant inputs in setting up ForCLIM that are likely to be used to develop a meta-model to simulate impacts and adaptation under high-end scenarios are:

- Environmental conditions:
  - Current climate (baseline scenario): monthly values of
    - Mean temperature and precipitation, T_m(month) and P_m(month);
    - Standard deviation of these mean values, T_{sd}(month) and P_{sd}(month);
    - Correlations between precipitations and temperature (rTP (month)).
  - Future climate: seasonal delta values (difference between baseline climate and future climate)
    - Mean delta in temperature and precipitation, ΔT_m(season) and ΔP_m(season);
    - Standard deviation of these mean values, ΔT_{sd}(season) and ΔP_{sd}(season);
    - Correlations between seasonal delta in precipitations and temperature (rΔTP (season).
  - Soil
    - Soil water content (bucket size, cm);
    - Available nitrogen (kgN/ha).
- Forest state:
  - Species (individual species in a first time, possible inclusion of multiple species mixture);
  - Structure / stage at t : uneven-size *vs.* even-sized (and stages represented).

The description of the forest state might be modified depending on the time-dependency approach, i.e. the way the current forest state depends on past state (species and past management, i.e. if unmanaged or managed) and will influence future forest state:

- Management:
  - Unmanaged forests: "natural forests" at equilibrium with climate;
  - Managed forests: even-aged or uneven-aged management regime; in both case thinning/harvesting frequency and intensity must be adapted to species and climate.

3. Outputs

The most relevant ForClim outputs for inclusion in the rIAM are:

- Timber production: timber volume harvested each year, possibly detailed per species and diameter/size class to affect different prices;
- Forest structure: diameter distribution per species, which indicates the structure of the forest (in case it is used to define forest state for time-dependency);
- Forest stocking : total biomass and/or basal area (per species if mixed forests), carbon stock.

It should be noted that other relevant forest outputs, such as the total area of forest, area of managed forest, tree species diversity etc. will be output through the rural land use allocation model.

3.5.2. **Policy relevance of the Forest meta-model within the rIAM**

The forest meta-model will be relevant in understanding the impacts of, and adaptation to, high-end scenarios within the broader landscape, and to inform the role of such changes in forests to the EU Forest Strategy and the Habitats Directive:

1. Species change

The main adaptation options will be to change the species that is regenerated (tree species that are being planted in the case of even-aged system, or naturally regenerated in case of uneven-aged management– indirectly simulated by controlling the list of species that will appear naturally). The idea is to favor the establishment of species that are more adapted to future climatic conditions, and thus to shorter the transition to a new sustainable forest composition (compared to "natural" change in forest composition) and reduce the risks associated with impacts from increased temperatures and drought on current (non-adapted) forest species.

Another possible (but more complex to implement) adaptation option would be to increase forest biodiversity and resilience by increasing the diversity of tree species, i.e. to regenerate forest with a mix of tree species at the stand scale (forest management unit). The mix will be based on current species and/or may include species which are more adapted to future climatic conditions (in the case of strong impacts of climate change on current species, these more "future-adapted" species will take over and thus limit dieback at the scale of the forest management units).

2. Shortening rotation length

Finally, shortening the rotation length (i.e. lowering the target diameter) might be seen as an adaptation measure to reduce the vulnerability of forests to climate change (reduce exposure time to natural hazards), especially if the species is affected by climate change. This could also be an option to accelerate the transition from a non-adapted species to a more adapted species.

3.6. Crop yield

The crop yield meta-model will be developed from outputs derived using Yield-SAFE (**YI**eld **E**stimator for **L**ong term **D**esign of **S**ilvoarable **A**gro**F**orestry in **E**urope), a process-based model used to predict long-term crop yields (Van de Werf et al. 2007). Yield-SAFE operates on a daily time step using parameter sparse equations to simulate growth and dry matter production using mean temperature, radiation and precipitation inputs. The model is designed to provide ecophysiologically based simulations of average annual crop growth based on a limited number of parameters (Graves et al. 2010) therefore making it suitable for application across Europe. Crop development is determined by planting date and temperature sum, which determines potential biomass accumulation. Availability of water (dependent on soil properties, precipitation, evaporation and crop water uptake) limits biomass production.

3.6.1. Development of the crop yield meta-model

Yield-SAFE has been applied across Europe (0.5 degree grid) with daily meteorological input data from 1995-2013 inclusive from the E-OBS dataset (Haylock et al. 2008), and calibrated against observed crop yields at the NUTS 2 and national levels from the Eurostat database from 1995-2000. The model estimates potential and water-limited annual yields for each crop (tonnes per hectare), and variance of annual yield throughout the simulation period. The model has been calibrated (similarly to previous studies, e.g. Graves et al. 2007; Van de Werf et al. 2007; Keesman et al. 2011) for the following crop types:

- Wheat
- Winter Barley
- Spring Barley
- Oilseed rape
- Potatoes
- Maize
- Winter Beans
- Spring Beans
- Sugar Beet
- Sunflower
- Grassland

- Olives
- Soya

A meta-model is being developed for each of the crops listed, using a step-wise multiple regression analysis between Yield-SAFE outputs and influential input variables. Soil water content and a range of meteorological variables at various temporal resolutions were entered into the preliminary meta-model. Those variables found to have an insignificant influence on yield are being excluded from the final meta-models. The current version of YieldSAFE does not include representation of heat stress, so heat stress will be incorporated into the model in a similar way to the existing representation of water stress to improve the accuracy of yield estimation under high-end scenarios. Adaptation responses to high-end scenarios to be implemented within the crop meta-model will include development of drought/heat tolerant species varieties (based on modified sensitivity to soil water and high temperatures), and changes of harvest and sowing dates.

For each decadal iteration of the rIAM, the meta-models will output the yield per unit area for each crop type, and the variability of the yield throughout the decade, for use by the rural land allocation model. The meta-models will provide both potential and water-limited yield, and will account for the influence of changing CO_2 concentrations on crop yields. Time-dependency within the meta-models is not an issue as yields in one decade do not depend on the previous decade.

3.7. Rural land use allocation

The rural land use allocation model allocates rural land to a range of agricultural, forest and unmanaged land uses based on profitability and demand, and is based on the meta-SFARMOD meta-model implemented within the CLIMSAVE IAP (Audsley et al. 2015). It utilises outputs from the urban, crop yield, forest, water resources and flood meta-models to make this allocation.

3.7.1. Changes to meta-SFARMOD within the rIAM

To accommodate the time-dependent nature of the rIAM and to better represent different rural land uses, a number of modifications and improvements are being made to meta-SFARMOD:

- Possible rural land uses are being expanded to cover arable, dairy, extensive (grassland), managed forestry, unmanaged forestry, very extensive and abandoned.
- In the allocation of land uses to soils within grid cells, the profitability thresholds between land use classes were sharp cut off values. For example, the profitability threshold for intensive agriculture of >€350/ha meant that if the profitability of a soil cell was €351 then it was classed as intensive, if €349 then extensive. This has been improved so only a proportion of the soil cell is allocated to each use which increases as the profitability above the threshold increases – so for a profitability of €351/ha, it will be assumed that 51% is intensive and 49% extensive respectively.
- The model operates at decadal time steps as opposed to the independent timeslices within the IAP. To recognise the barriers and timelags in land use change, it is assumed that only a proportion of the soil cell changes to the new land uses determined by the profitability in the timestep, but that after 45 years, the proportion will be close to 100%.
- The use of ten year time steps means that we need to consider the rate of change between different land uses. It is not reasonable for there to be abrupt changes from say forestry to intensive arable over a wide area. To deal with this each possible land use transition is given values for: (a) additional capital investment required; (b) lower yields with greater risk in the earlier years as know-how is acquired and agronomy optimized; and (c) a maximum rate of change per decade. The net present value (NPV) of the possible land use changes will be

calculated using discounted cash flow (DCF) techniques. If the NPV exceeds the threshold then change occurs.

3.7.2. Policy relevance of meta-SFARMOD within the rIAM

The Common Agricultural Policy (CAP) is the most relevant policy area for meta-Sfarmod, although rural land use contributes to many other European policies including the Water Framework Directive, the Floods Directive, the Habitat Directive and the EU Forestry Strategy. The objectives of the CAP are set out in Article 39 of the Treaty on the Functioning of the European Union and are to ensure a fair standard of living for the agricultural community and to assure the availability of food supplies at reasonable prices. In addition to indicators on production and prices the CAP is increasingly tied to sustainability and a set of agri-environmental indicators are proposed (http://ec.europa.eu/eurostat/web/agri-environmental-indicators/analytical-framework). The most policy effective rIAM output indicators are likely to correspond closely to existing EuroStat policy indicators, although the rIAM will also generate outputs that are relevant, but not well captured in official statistics:

- Main commodity production: wheat, sugar beet, oilseed rape, potatoes, sunflower, red meat production, and white meat production;
- Main commodity group prices: wheat and cereals, and oilseeds.

Potential agri-environment indicators from rIAM meta-sfarmod laid-out in the DPSIR (Drivers - Pressures - State - Impact - Responses) analytical framework:

- Drivers (input use): Irrigation water, fertiliser nitrogen, and (herbicide use);
- Drivers (land use): land use change, cropping patterns, and livestock patterns;
- Drivers (farm management): soil cover, and fallow area;
- Drivers (trends): Abandoned land area, intensive area, and extensive area;
- Pressures (resource depletion): Water abstraction;
- Pressures (benefits): Renewable energy production;
- State/Impact (natural resources): Nitrate water pollution;
- Responses: Protected areas.

In understanding how European agricultural and forest sectors may respond to high-end climate change, the most effective agricultural adaptation responses will boost production in the face of increasingly adverse climatic and land quality conditions whilst keeping prices, input resource use, ecosystems services, and pollution within reasonable limits. However, there are other adaptation options that can contribute to delivery of the Water Framework Directive, Habitats Directive and the EU Forest Strategy. The following are a list of the most important responses and drivers that can be simulated by meta-SFARMOD:

- Increase in agricultural yields;
- Increase in irrigation efficiency;
- Increase in agricultural efficiency due to mechanization;
- Changes in land allocated to set-aside/buffer strips/beetle banks;
- Changes in arable land used for biofuel production;
- Increase in importance of wood for fuel;
- Changes in dietary preferences for red (beef and lamb) and white (chicken and pork) meat;
- Changes in food imports;
- Reducing diffuse source pollution from agriculture.

3.8. Biodiversity, including Protected Areas

The biodiversity modelling in the rIAM focuses on simulation of the distribution of a range of species representing different European habitats and changes in the Natura 2000 protected area network. It takes account of habitat availability, through the outputs of the land use allocation model and the extent of Protected Areas.

3.8.1. Changes to the SPECIES model within the rIAM

The SPECIES model in the CLIMSAVE IAP takes climatic/soil information and produces climatic suitability maps from this data. The presence of appropriate conditions for a given species are provided by: (a) appropriate climate space; and (b) appropriate climate and habitat space. In the CLIMSAVE IAP the time steps are independent from one another so that it is possible for a cell to become unsuitable in the 2020s and then suitable again in the 2050s.

The new IMPRESSIONS version will be refined in several ways.

1. High-end climate change
The existing SPECIES model can already simulate the effects of average annual temperature increases of up to +8^{o}C as the temperature range covered by the model's training data within Europe and North Africa is from -17.6^{o}C to 37.4^{o}C. Under extreme climate scenarios for RCP8.5 no grid cells move out of the training range with respect to temperature so it is considered unnecessary to retrain the 118 existing species networks.

2. Time-dependency
Presence/Absence (P/A) values (driven by both climate and habitat) from the previous time slice (rather than baseline) will be used to determine if a cell is: (a) stable (i.e. no change); (b) a 'gain' of new potential space; or (c) a 'loss' of space. At each future time step, a probability surface of climate suitability for the species will be combined with a habitat weighting to produce a "habitat-weighted climate suitability surface". In grid cells where the species is present in the previous time step but the habitat-weighted climate suitability surface is zero the species is considered lost; unable to survive due to habitat/climate stress. In all other cells the species is considered to remain present.

A new dispersal model is being developed to simulate how species may be able to access newly available climate/habitat space. The model will be informed by the dispersal capabilities of each species to determine whether the species can reach these new areas. The dispersal code will use the habitat-weighted suitability surface to identify dispersal direction and combine this with the species locations from the previous time step and their dispersal abilities to map a new distribution of the species for the current time step. This method will allow not only the mapping of species presence / absence but the probable drivers of change to be identified in terms of climate change, habitat change or dispersal ability.

3. Better representation of habitats
In the CLIMSAVE IAP, species were masked by either the presence of SFARMOD's arable land (for cereal field margin species), forests (for forest species) or CFFlood's wetland classes (for wetland species). In rIAM climatic and soil-based rules will be used to better separate the following additional classes and sub-classes: heathlands (following Gimingham et al. 1979a); bogs/peatlands (following Clarke et al. 2010) and natural grasslands (acid, neutral, calcareous following Gimingham et al. 1979b).

4. More representative species

Revised species selection will be based on an awareness of the species with available dispersal information as well as ensuring we cover a reasonable sample of dominant species for all habitats. Increasing the number of species will increase the biodiversity representativeness and considerably improve the biodiversity vulnerability index and any ecosystem service outputs dependent on it.

5. Improved biodiversity summary indicators

The summary indicator used in the CLIMSAVE IAP based on a mixed representative species group of 12 ecologically significant/charismatic species from a range of habitats will be replaced by the vulnerability by habitat (i.e. forest vulnerability, arable vulnerability, heathland vulnerability, etc.) following Dunford et al. (2015a). These will represent the key policy-relevant model indicator(s) to be used for the biodiversity model in rIAM. We will also investigate a "trigger" threshold for the chosen indicator(s) that represents a need for adaptation. We intend for this to be related to the change in total area covered by the species of interest (i.e. the sum of stable area + dispersal-driven growth for the time step as restricted by both climate and habitat).

3.8.2. Changes to the Protected Area model within the rIAM

The Protected Areas (PA) model currently modifies the PA coverage from that of Natura 2000 by selecting the: (a) amount of new PA to be created (relative to baseline); and (b) the split of this between habitats (in the CLIMSAVE IAP this was forest, unmanaged and extensive grassland). The PA is then allocated to these classes dependent on the baseline distribution of land use and a choice between: (a) whether or not the PA is targeted at expanding existing areas, e.g. "buffering"; or (b) whether or not the PA is targeted at creating new areas where there currently isn't any, i.e. enhancing "connectivity".

Within rIAM, future PA allocations will be based on the previous decade's PA distribution rather than that of the baseline. The PA model will be re-fed the data for the decade before to enable land use change to happen before PA is allocated and the amount of PA to be created in a 10-year period, rather than over the full time period, will be calculated and supplied by the central adaptation module. Furthermore, the new land use classes created for the SPECIES model (see section 3.8.1) will be taken into consideration. A new file of the baseline distribution of PA by these habitats will be created and supplied to the land use allocation models (RUG and SFARMOD) for them to take into consideration when allocating land. The new adaptation module will need to implement the changes in PA in response to pressures on biodiversity. This module will determine how PA responds to situations where a trigger variable exceeds its threshold (i.e. a limit of biodiversity loss is reached that triggers adaptation action), what form this adaptation will take and when the "vision" is achieved (see Section 3.10).

3.8.3. Policy relevance of the SPECIES and Protected areas models within the rIAM

The ability to simulate the impacts of climate and land use change on multiple species across Europe has clear relevance to understanding the implications of future change for the Habitats Directive and to aspects of the management of natural resources under the CAP. The effectiveness of alternative policy responses such as changing the Protected Area network or modifying future land use to enhance habitat availability will inform an improved understanding of the robustness of current policies under high-end scenarios.

3.9. Coping capacity module

The concept of coping capacity is grounded in Porrit (2006)'s 'five capitals' model of resource availability. It reflects the resources, both tangible and societal, available to help individuals within society cope with the impacts of climate and socio-economic change. Coping capacity within the CLIMSAVE IAP was defined as being based on the stocks of capital a society has available to deal with either the *potential impact* (i.e. before adaptation) or the *residual impact:* (i.e. after adaptation). Coping capacity is used to identify areas that are either not vulnerable, because the potential/residual impact is too low (A on Figure 3.7), not vulnerable because there is sufficient coping capacity (B), vulnerable as there is not enough coping capacity (C) or vulnerable because the impact is too high to ever be coped with (D).

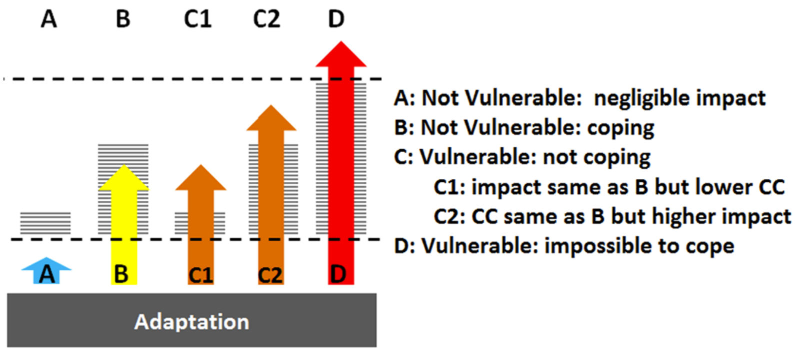


Figure 3.7: Coping capacity (reproduced from Dunford et al. 2015b).

The coping capacity model in the CLIMSAVE IAP follows an indicator-based approach that calculates values of four capitals: human, social, financial and manufactured. The fifth capital: natural (naturally occurring resources) was not included in the coping capacity model as it was already considered by the integrated biophysical modelling. The eight indicators used for the other capitals are:

- Human capital: Life expectancy; Tertiary Education;
- Social capital: Income inequality; Help when threatened;
- Financial capital: Household income; Net household savings rate;
- Manufactured capital: Transport and Produced capital.

Equal weightings are used to combine the indicators per capital and then the capitals into an overall index of coping capacity. These capitals were also used to constrain the ability to adapt, based on the identified limiting capital for each adaptation option within the IAP.

3.9.1. Changes to the coping capacity model within the rIAM

In rIAM, the availability of more detailed socio-economic modelling and the time-dependency of the platform provide new opportunities to further extend the coping capacity model. A number of key parameters from the socio-economic scenarios and the outputs from the revised models have been identified as potential inputs from which coping capacity can be defined. These include:

- Human capital:
    - mortality rate from the health model;
    - education level, number of retired people and number of working age people from the urban model.

- Social capital:
  - social preference and inequality (ratio of high to low education level) from the urban model;
  - governance type from the SSP storylines.
- Financial capital:
  - downscaled GDP from the urban model;
  - other variables available in existing databases: e.g. IIASA/GTAP.
- Manufacturing capital:
  - transport infrastructure as a time-distance indicator and changes in commercial/industrial land from the urban model;
  - flood protection standards from the flooding model.

Possibilities for including natural capital in the coping capacity index will be explored taking account of whether variables can be identified from the revised rIAM sectoral models to represent this capital which do not create problems of double-counting in relation to impact indicators. For example, these could include land not currently used for intensive production, surplus abandoned land (i.e. land with potential but surplus to requirements), and total biomass of trees and crops.

By including these dynamic modelled indicators it will be possible to move away from the time-slice approach of the CLIMSAVE IAP. Thresholds of coping will be developed for each of these indicators (following Dunford et al. 2015b): these require the identification of the level of potential/residual impact where coping begins to be needed and where a potential/residual impact is too great that no matter how much resources are available it is impossible not to be made vulnerable by the impact (the upper and lower coping threshold in Figure 3.8). These limits will be linked to the adaptation triggers used within the central adaptation module (see Section 3.10).

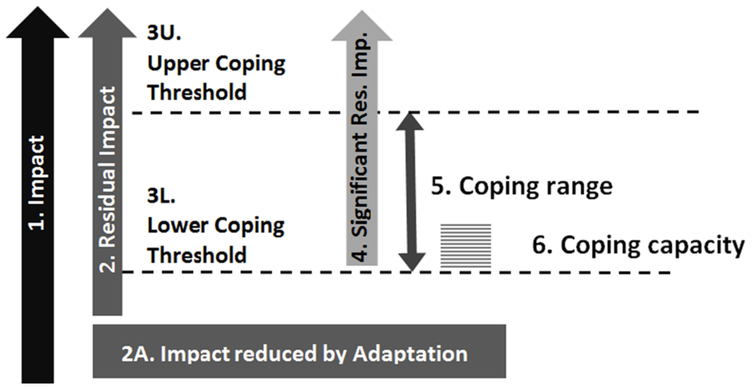


Figure 3.8: Coping capacity methodology (reproduced from Dunford et al. 2015b).

Finally, we will explore computing coping capacity for different social groups to better represent those SSPs with high inequality, and whether it will be possible to develop different weighting of capitals in terms of their contribution to coping capacity either in relation to: (a) the type of problem/impact they are coping with; or (b) the parts of society that is attempting to cope.

3.10. Adaptation module

3.10.1. Representation of adaptation within the rIAM

The representation of adaptation in the rIAM is a development of that implemented in the CLIMSAVE IAP to provide a more realistic representation of the adaptation process. This recognises that implementation of a particular adaptation measure:

- Is triggered by something;
- Does not necessarily happen quickly (i.e. within a given time period) due to delays arising from planning, construction, uptake etc.;
- Does not necessarily happen to the full potential, because of a range of constraints (behavioural, social, financial, etc.);
- May not be important within, or compatible with, a particular storyline.

As a consequence each adaptation measure within the rIAM will have the following scenario-independent characteristics specified (Figure 3.9):

- Timelag from trigger to start of an effect;
- Time from trigger to achieving maximum effect;
- Potential efficacy under no constraints;
- The type of capital (human, social, manufacturing, financial) that has the greatest capacity to limit the implementation or efficacy of the option.

The efficacy of a given adaptation option under a particular scenario is reduced to the actual response using the approach adopted in CLIMSAVE, based on both the importance of the adaptation option within the scenario narrative and the availability of the limiting capital (Table 3.4). In situations where the limiting capital decreases over time, it is assumed that the effectiveness of the implemented adaptation option will also decrease (Figure 3.10).

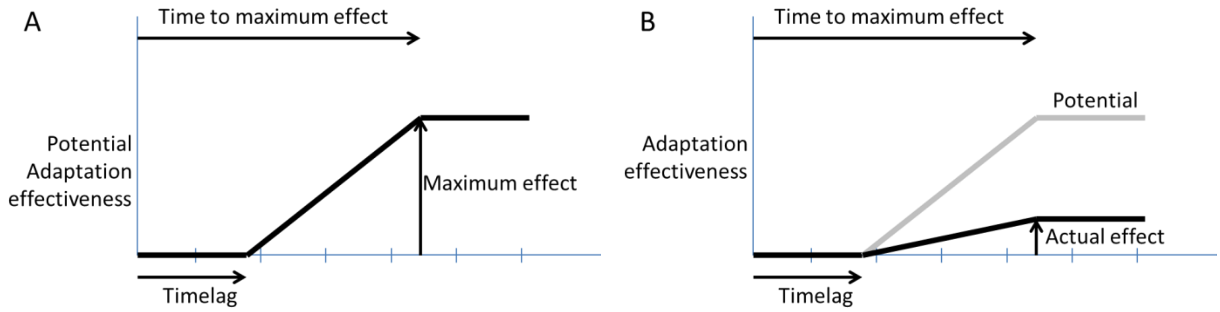


Figure 3.9: Idealised shape of an adaptation response under: (A) unconstrained and (B) scenario-dependent constraints.

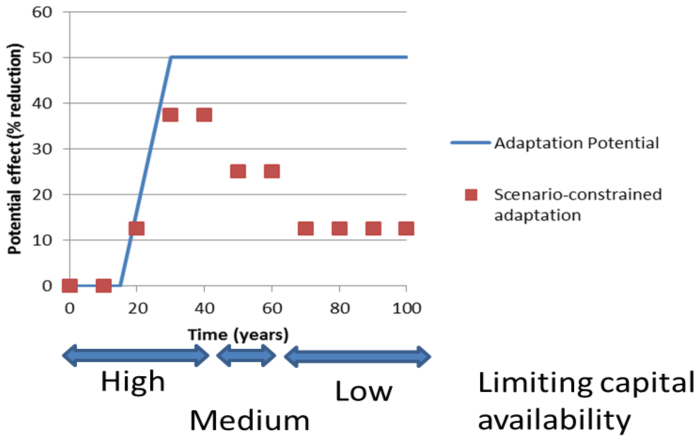


Figure 3.10: Representation of adaptation potential and scenario-constrained actual adaptation under conditions of reducing availability of the limiting capital [using Table 3.4].

Table 3.4: Assumed efficacy of actual adaptation as a percentage of potential according to scenario constraints (linked to adaptive capacity) and scenario.

Actual adaptation (% of potential)	Adaptive capacity (based on class of limiting capital)				
Importance of adaptation option within scenario:	Very low	Low	Medium	High	Very High
Low	5	10	25	50	75
Medium	10	25	50	75	90
High	25	50	75	90	95

3.10.2. Description of the Adaptation module

The time-dependent nature of the rIAM and the new software architecture will mean that manual implementation of adaptation (using sliders, buttons, etc.) as in the CLIMSAVE IAP is impractical. Instead, the adaptation strategy will be specified at the start of the run and a new adaptation module developed to implement the adaptation strategy specified in the model run settings sent by the User Input Module (Figure 2.2). It is proposed that the user will specify the following for each model run:

- The selected indicator that would trigger the need for adaptation:
  - Either an impact indicator or a vulnerability indicator;
  - There are likely to be a limited number of indicators (around one per sector)[3], for example:
    - Food security - based on thresholds of food production;
    - Water security- based on thresholds of the water exploitation index;
    - Biodiversity - based on thresholds of species losing climate/habitat space;
    - Forested area - based on thresholds of forest area;
    - Landscape - based on thresholds of landscape diversity;
    - Flooding - based on thresholds of people flooded;
    - Health – based on thresholds of people affected by heat?
  - Pragmatically, it is proposed that only one indicator can be selected in a given run, to enable sectoral trade-offs to be identified (rather than identify cross-sectorally

[3] In the CLIMSAVE IAP, there are 6 vulnerability indicators - food provisioning, water exploitation index, flood index, biodiversity index, intensity Index and land use diversity index. Further/different indices, and default thresholds, may be identified in IMPRESSIONS.

optimised adaptation strategies) – i.e. does sectoral adaptation to avoid exceeding a given indicator's critical threshold value cause unintended consequences (beneficial or adverse) on the other vulnerability indicators?

- The critical threshold value for that indicator that would trigger some form of response – default values for these thresholds would be determined by the research team, but the user will be allowed to change the default value (or specify the trigger as % of given critical threshold value).
- The value for the indicator that represents the vision being achieved.
- The adaptation pathway to enable a clear link to the WP4/5 transition pathways:
    - For the given indicator, only a selection of relevant adaptation options will be available;
    - These can be specified to be implemented pro-actively, reactively or not at all, relative to the timing of the exceedance of the critical threshold value for the impact/vulnerability indicator.

It is proposed to implement two alternative approaches to the design of the adaptation strategy (Figure 3.11), which can link to the WP4/5 transition and adaptation pathways. These are based on:

1. Specifying the actual decade when each adaptation measure is implemented;
2. Specifying the timing of the implementation of each adaptation measure relative to the timing of exceedance of the impact or vulnerability indicator threshold.

The running module will run the individual meta-models in the sequence from RUG to Coping Capacity (Figure 2.3) and will then run the Adaptation Module to implement the required adaptation according to the selected strategy.

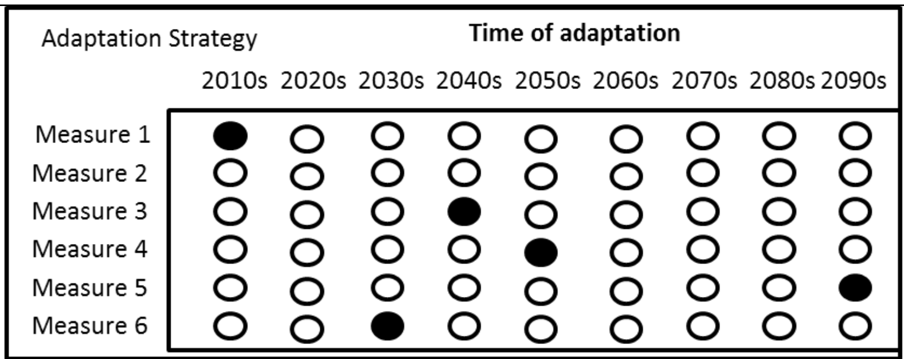
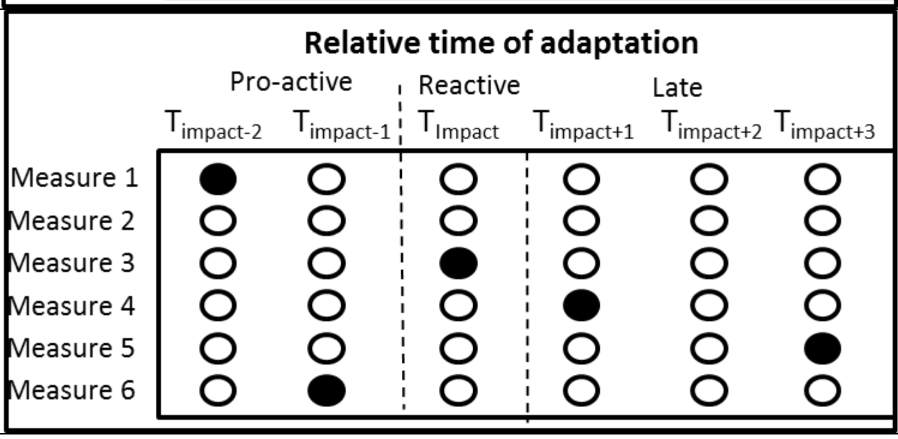
1) Specifying the adaptation timing as the <u>decade</u> in which measures are implemented	
2) Specifying the adaptation timing <u>relative</u> to the timing of impact / vulnerability	

Figure 3.11: Schematic examples of approaches to defining the timing of implementation of adaptation measures within an adaptation strategy in the client-side User Input Module.

4. Specification for the process-based impact modelling within Europe

Task 3B.2 will evaluate how any loss of information from using a simplified modelling approach (as in Task 3B.1) weighs against the gains in understanding of cross-sectoral interactions. The process-based modelling activities have three potential objectives:

1. Evaluating the effects of hydrological model uncertainty under high-end scenarios (HES) for selected basins, comparing the loss of model performance of emulators (meta-models) compared to the full model version (e.g. WGMM vs WaterGAP) and across model types such as emulator (WGMM), conceptual (WaterGAP) and process-based (SWIM) models;
2. Evaluating the hydrological impacts of 'dynamic' land use change under HES in selected river basins using SWIM driven by 'static' land use for time slices of 25-30 years, and by changes in modelled land use distribution obtained from the European case study modelling or from land use modelling in the regional case studies (See Deliverable 3C.1);
3. Evaluating the hydrological impacts of changing climate, including extreme events, under HES.

SWIM has been set-up for a set of representative basins across Europe (Figure 4.1), selected to link to the regional case studies of WP3C (Scotland, Hungary and Iberia), and to also include the different geographical regions across Europe (Table 4.1).

Table 4.1: Representative river basins being modelled by SWIM.

River	Case Study	State of model	Additonal data/information needed
Danube	Hungarian	Set up, calibrated and validated	To decide which SWIM *outputs* might be useful
Tagus	Iberian	Set up, calibrated and validated. Reservoir management included - 15 reservoirs in total. First impact assessments for ISI-MIP. RCP 4.5	Crop management, crop types, hydropower production rates (Spanish side)
Tay	Scottish	Set up until gauge Ballathie. First calibration and validation results	Datasets for reservoirs parametrization, crop management
Lule	European	Set up, calibrated and validated. Water management included, 5 reservoirs in total	Additional information is needed for reservoirs volume-area-depth dependencies
Eman		Set up, calibrated and validated	No
Rhine		Set up, calibrated an validated; studies for other projects already conducted	No
Ladoga Lake catchment	*European*	*Data collection, analysis of possible modelling extents.*	No

4.1. The SWIM model description, input data and outputs

The Soil and Water Integrated Model SWIM is a process-based deterministic eco-hydrological model, developed based on two previously created models: SWAT and MATSALU and described in Krysanova et al. (1998, 2000), which enables representation of the components of the hydrological cycle and related processes at the river basin scale.

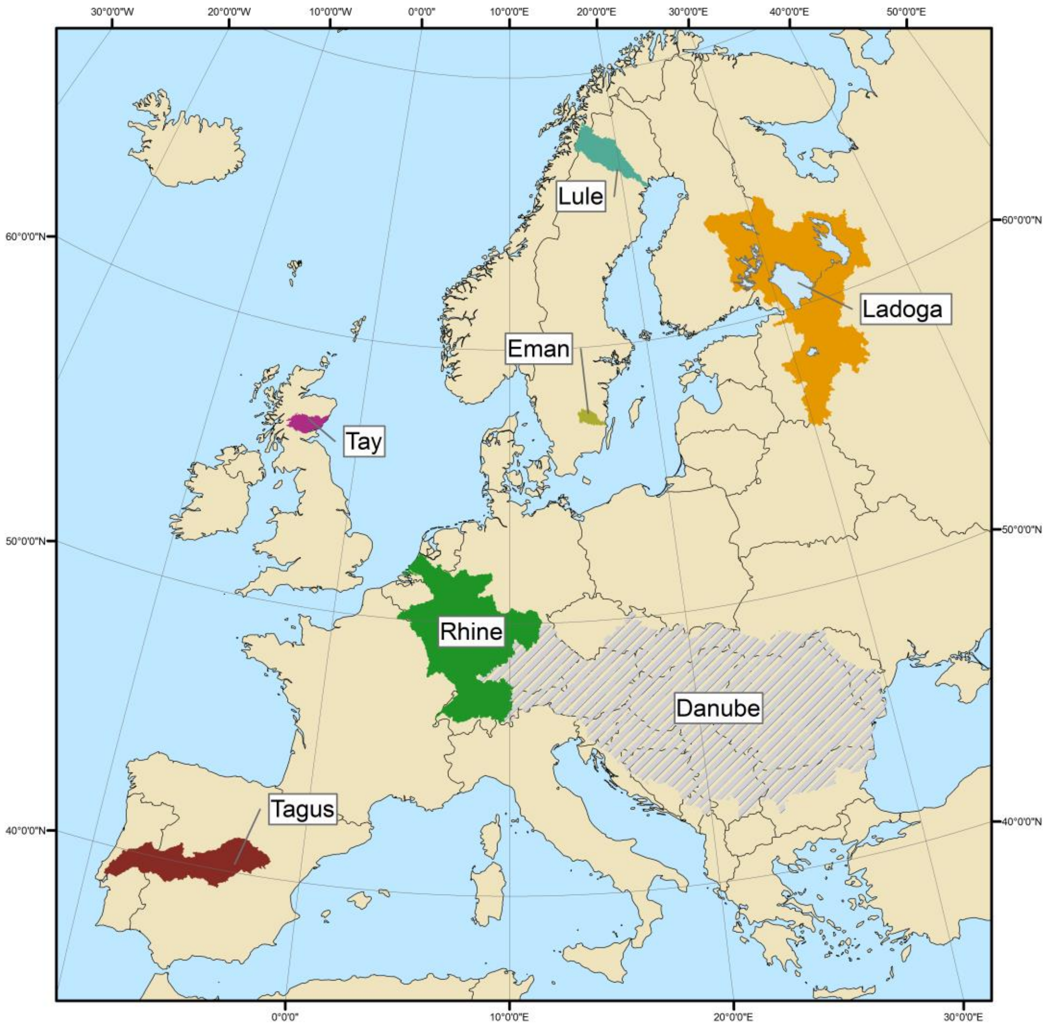


Figure 4.1: River basins being simulated by the SWIM process-based model.

The SWIM model consists of an assemblage of numerical representations of physical processes of the hydrological cycle and other related processes (vegetation growth, nutrient cycling, and erosion). These physical processes are mathematically interpreted with different levels of complexity and form four main modules of the model: hydrological, groundwater, biogeochemical and plant growth modules (schematically represented in Figure 4.2). SWIM operates on a daily-time step and uses climatic, land use, topographic and soil datasets as input files (see Table 4.2 for more detailed descriptions of necessary and additional input datasets).

The topographical map of a catchment serves as a basis to create a sub-basin map, which is later intersected with land use and soil maps, to identify so-called HRU's – Hydrological Response Units – areas within each sub-basin, where a unique combination of land use and soil type is present. Identical HRUs, the ones which have same land use and soil types are assumed to have the same hydrological "behaviour" and are later combined into hydrotope classes within each sub-basin. The components of the hydrological cycle, nutrient cycling and sediment loads are calculated at the HRU level and added together for sub-basins. After that the lateral flows of water, nutrients and sediments are routed through the basin, using conceptual representation of the open channel hydraulics – the Muskinghum method, taking into account transmission losses.

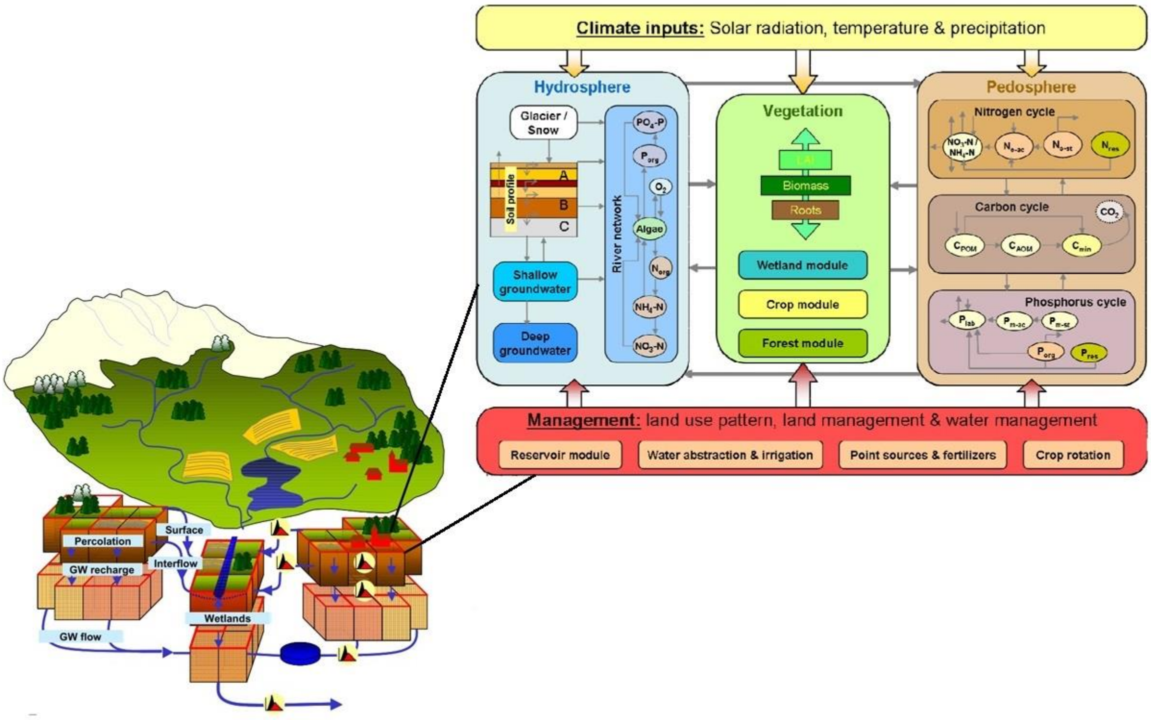


Figure 4.2: SWIM schematic representation.

After setting up the model using area-specific input forcing datasets, the calibration and validation phase starts. The SWIM model has been calibrated and validated against the observed discharge data series at a daily or monthly time step. There are two main criteria of fit between the observed and simulated discharges: the Relative Volume Error – RVE, and the Nash-Sutcliff Efficiency – NSE. The RVE is a total deviation in the volume of water discharged, expressed in percentage, and the NSE is an efficiency coefficient, which relates a sum of squared differences between the observed and simulated discharges to the variance of the observed values of discharge. The RVE coefficient can vary from -100% to +∞, where 0 indicates a perfect fit, and the NSE coefficient from -∞ to 1.0, where 1 indicates a perfect fit. The specific limits for both criteria, which correspond to a "good" performance of the model are given by Moriasi et al. (2007).

4.2. SWIM model outputs

SWIM outputs a range of indicators describing the state of the land and water. These include:

1. River discharge at the outlet of the whole river basin, and at the outlets of each sub-basin.
2. Nutrient (NO_3-N, NH_4-N, PO_4-P) concentrations and loads at the outlet of the whole river basin, and at the outlets of each sub-basin.
3. Leaf area index (LAI) dynamics and crop yields.
4. Sediment loads at the outlet of the whole river basin, and at the outlets of each sub-basin.
5. Hydropower production, volume of reservoirs.
6. Spatial outputs: components of the hydrological cycle: evapotranspiration, runoff, groundwater recharge at the HRU level within each sub-basin and precipitation at the sub-basin level as long-term annual average values.

Table 4.2: Input datasets needed to set-up and run SWIM (please note datasets required for water quality are not listed here).

N	Datasets	Type	Comments
	Spatial		
1	DEM – Digital Elevation Model	raster file (ASCII)	
2	Land use map (raster file (ASCII))	raster file (ASCII)	Current management strategy (land use change in the catchment)
3a	Soil map (raster file (ASCII))	raster file (ASCII)	
3b	Soil parameters		Depth of the layer (mm) Clay, silt, sand content (%) Bulk density (g/cm3) Porosity (Vol, %) Available water capacity (Vol, %) Field capacity (Vol, %) Organic carbon content (Vol, %) Organic N content (Vol, %) Saturated conductivity (mm/hr)
4	Map of major reservoirs in the basin (shape file)	vector file (shape)	or their coordinates
5	Map of existing gauges	vector file (shape)	or their coordinates
7	Map of river network, basin and sub-basin boundaries	vector file (shape)	for comparison, shape file
8	Map of climate and precipitation stations	vector file (shape)	
	Relational		
1	Climate data (Temperature, Precipitation, Humidity, Solar Radiation)	continuous datasets	As many stations as possible; daily solar radiation; relative humidity; minimum, maximum, average day temperature; daily precipitation
2	River discharge at the basin outlet, sub-basins	continuous datasets	Daily or monthly discharge time series, only for calibration / validation
3	Crop types, crop management and crop rotation		Which crops are in the basin, dates of planting/harvesting, dates/rates of fertilization. Current and future management strategies.
4	Reservoir management		Type of reservoir, daily/monthly discharge data series, daily/monthly withdrawals data series
5	River cross-sections		If exists, in several points of the basin, for comparison

5. Specification for the new agent-based model for Europe

Task 3B.3 covers three areas of work:

- Development of a new agent-based model (ABM) for Europe which simulates institutional behaviour through time with respect to climate change;
- Specification of the different ABMs in IMPRESSIONS (CRAFTY, LAGOM, etc.);
- The use of the ABM models to explore the WP4/5 transition pathways towards achieving the visions of the European and regional case studies.

Similarly to Task 3B.2, Task 3B.3 will provide more detailed modelling than is possible with the rIAM, and so explore the potential for effects not considered by the simplified cross-sectoral models. It will also provide information for the cross-sectoral models to use when simulating different adaptation options, through soft-links between agent-based and rIAM models. Finally, it will produce alternative assessments of the development of socio-economic systems through a combination of the sectoral ABMs involved in IMPRESSIONS.

5.1. Model roles and developments

ABMs within IMPRESSIONS will provide a range of results at case study, European and global scales. The principal model to be developed and used at the European scale is the CRAFTY model of land use change, but findings from the global-scale family of ENGAGE, DSK and LAGOM ABMs (WP5) will inform this process through soft-links between the models. Together, these models will simulate European land use dynamics under a range of scenarios, governance strategies and institutional interventions in order to explore development of the European land system. This will contribute to analysis of tranistion pathways developed in WPs 4 and 5, focusing on the extent to which stakeholder-developed visions can be achieved under climate change.

The majority of ABM model development activity will occur within CRAFTY (with development of the global ABMs being part of WP5). CRAFTY currently operates at the European scale on the basis of exogenous climatic, socio-economic and demographic drivers of land use change, and the behaviour and decision-making of individual land managers (modelled as autonomous agents). Land manager agents are defined in terms of their ability to produce ecosystem services, sensitivity to profit, dedication to their land use, social network connections, willingness to adopt innovations and a number of other personal and cultural factors that can be varied depending on model context and objectives. Land management results in the production of ecosystem services and can also change the productive potential of the land, affecting subsequent land use decisions. Societal demands for ecosystem services reflect demographic, socio-economic and trading conditions, and generate competition for land between agents.

During the IMPRESSIONS project, CRAFTY is being further developed to incorporate the behaviour of institutions concerned with land use and climate change. These institutions will be modelled endogenously, as a separate class of autonomous agents with defined objectives and abilities to intervene in the land system, which can monitor and act upon processes of land use change (see Figures 5.1 and 5.2). Institutions will primarily interact with land manager agents by disseminating knowledge and technology through social networks, by subsidising or proscribing certain land uses or land use transitions, and by altering levels of demand for particular ecosystem services. Both land manager and institutional agents respond to climate change as expressed through its effects on the productive potential of the land, and therefore on the ability of the land system to satisfy human requirements for ecosystem services.

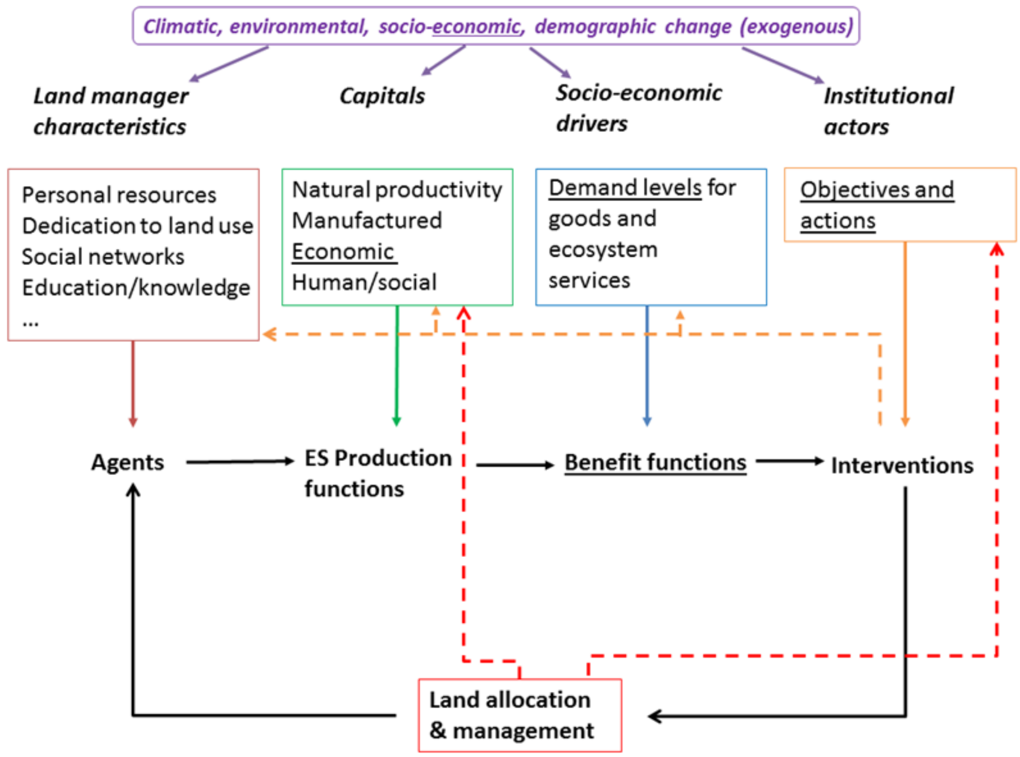


Figure 5.1: Schematic of the CRAFTY model. Inputs fall under four broad categories (top) and influence modelled processes at the points shown. Underlined terms indicate inputs from WP5 models. Agents are parameterised on the basis of census, literature and social survey data, and their ability to produce ecosystem services is defined via capitals describing potential productivity and observed production levels. The benefits or utilities of production depend upon the sizes, scales and forms of societal demands for ecosystem services. Institutions intervene at various stages in the modelled process and monitor subsequent changes in land management and service production. They also affect particular capital levels, which subsequently affect land use decisions. The solid black arrows represent model flow during one simulated time-step, set to the duration of land management decision-making (e.g. one year). Exogenous (scenario-based) changes impact upon the model at each stage and time-step.

Implementation of institutional agents is partially complete and remaining development will focus on allowing institutions to undertake an appropriate range of monitoring, deliberations and interventions, as defined by the data sources outlined below. Activity is therefore focused on concurrent gathering of data and information about relevant institutional actors and the development of code that allows their inclusion in CRAFTY. Further activity is centred on establishing links between model development, connected WPs and other modelling work within IMPRESSIONS (details below).

The family of ENGAGE, DSK and LAGOM models developed in WP5 have an economic focus, and will deal with the impacts of different climate policies at local, regional and global levels. Agents representing firms and households respond, within a modelled economy, to adaptation and mitigation policies initiated exogenously, and through their responses illustrate economic risks, opportunities, costs and benefits of different policies. The DSK model can be thought of as a more complete and coherent version of ENGAGE, where the co-evolution of the economy and the climate was neglected. DSK is composed of heterogeneous firms, which are grouped into two vertically separated manufacturing industries that receive credit from a unique central bank. Firms are fueled by an energy sector, which, as an aggregate, constitutes the principal CO_2 emission contributor. The link between CO_2 concentrations in the atmosphere and the Earth's surface temperature is modelled non-linearly and, as the temperature increases, stochastic damages affect both labour productivity and the stock of capital. Such damages include both frequent and mild environmental shocks as well as low-probability, but extreme climate events. Technical change occurs both in the manufacturing and energy side of the economy. Innovations and learning contribute to determining the cost of energy produced by differently carbon-intensive technologies, which, in turn, affects the energy-technology production mix and the total amount of CO_2 emissions per unit of time. In this way, structural change in the economy is intimately linked to climate dynamics. The output of the model consists of an ensemble of micro and macro time series tracking the evolution of the system both from the climate and economic side.

The LAGOM family of models offers a complementary perspective as they take into account the input-output structure and its evolution, which emerges from the micro-economic interactions of firms. This allows: (a) representation of the sectoral effects of climate policy and its positive or negative impacts on macro-economic dynamics through input-output linkages; and (b) investigation of the spread and the aggregation of sectoral and/or geographical climate impacts through the production network. These economy-wide approaches are particularly relevant to Task 3B.3 in their implications for societal demands for ecosystem services, the magnitude and form of values attached to them, and the financial basis for their provision through active land management.

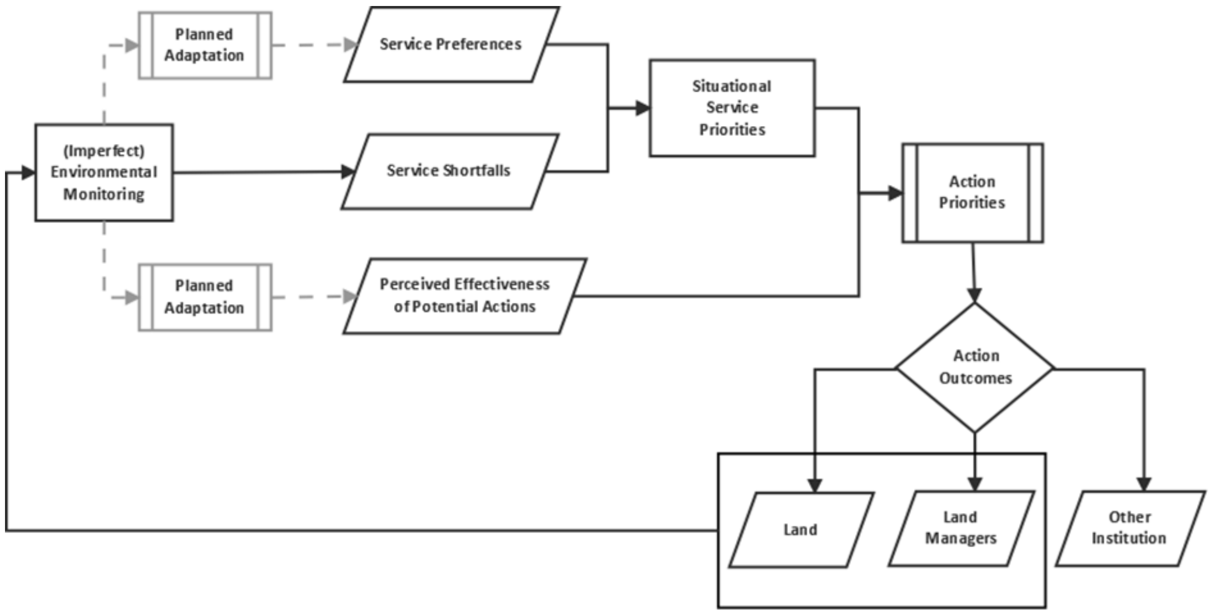


Figure 5.2: Schematic of the decision-making and intervention processes being implemented for institutional agents in CRAFTY. Institutions monitor service provision and compare against their defined preferences. Differences between current provision and preferences lead to situational priorities (which can be distinct from long-term priorities), which in turn drive the selection of actions from those available to the institution. Actions include a range of interventions, and institutions are able to learn about the effectiveness of their actions from subsequent monitoring. Grey boxes connected by dashed lines represent processes that occur only once every several loops.

5.2. Model inputs

This Task requires a number of model inputs to enable calibration of current and future (scenario-based) conditions. Current conditions are based on data underpinning the European application of CRAFTY, describing productive potential (via five capitals: human, social, financial, manufactured and natural capital), land manager and institutional agent characteristics, production functions, demand levels and benefit functions for ecosystem services, and feedbacks from land management to capital levels. The majority of these inputs are already included in the existing European CRAFTY model, but some will be altered for use in IMPRESSIONS and all are subject to change under the high-end climate scenarios used here.

Land manager agents are defined on the basis of literature analysis and meta-analysis, census and social survey data that describe the personal, social and cultural characteristics of land managers and the ways in which these characteristics affect land management practices. Basic parameterisation of these factors is complete but will continue as data sources with more detail and relevance are identified (particularly those relating to land managers' social networks, preferences and perceived scope for management decisions, sensitivities to ecosystem service delivery and interactions with institutional actors). The parameterisation of a population of institutional agents will be based on the empirical institutional analysis in WP1, used to specify the range of relevant institutional actors and types, their objectives and abilities to monitor and intervene in the land use system. Future institutional behaviour will be based on governance strategies associated with the scenarios, in particular those defined through Task 5.2, on the behaviour and policy options of institutions under high-end climate change.

Capital levels, describing the potential productivity of different ecosystem services, will be based on existing European data already incorporated in CRAFTY, adjusted where necessary for consistency with other modelling work within IMPRESSIONS (i.e. adoption of the same data sets where possible). Changes to capital values under the scenarios and adaptive pathways will be defined by Task 4.4 (linked to the work on capitals in rIAM, see Section 3.9) and, in the case of economic capital, by outputs from the WP5 economic ABMs. Changes to natural capital through time will also be informed by rIAM modelling results and by relationships characterising the impacts of land management on productive potential. The exploitation of capitals to provide ecosystem services will be described by (established) production functions based on analysis of existing land uses and their relationships to underlying capital levels.

Demand levels and benefit functions for ecosystem service provision will be empirically based but scenario dependent. Initial conditions (currently incorporated in the CRAFTY European model) reflect existing levels of demand and valuation for broad classes of ecosystem services produced by modelled agents. Future changes will be incorporated directly from scenario specifications or, in most cases, from simulation results of WP5 models, which will provide scenario implications for demand levels, output and industrial production dynamics, technological trajectories and, to some extent, benefit (utility) valuations.

5.3. Model evaluation and validation

The European CRAFTY model is subject to ongoing evaluation, including sensitivity and uncertainty analyses. These will continue as new data and processes are introduced, especially where data is insufficient for exact calibration, in order to explore possible outcomes and provide an understanding of sources and levels of uncertainty. Scenario analysis will also include experimental parameter variations within defined ranges. In addition to these quantitative methods of model evaluation, continuing assessments will be made of the consistency of model findings with stakeholder and expert opinion and with other relevant model outputs (including, where appropriate, those of the rIAM and WP5 ABMs such as land-based sectoral productivities, land use patterns and rates of change, etc.). Such assessments have already been used to evaluate the existing, basic European application of CRAFTY. Formal validation will focus on the model's ability to replicate key aspects of historical land use change (such as its spatial and temporal characteristics) and the responses of institutional actors to changes in environment, climate and ecosystem service provision. Of particular importance is validation of institutional behaviour, which will be partially undertaken in WP5 and partly via comparisons between results from this task, WP5, and historical observations.

The ENGAGE, DSK and LAGOM model family also undergoes a coupled input-output validation procedure. Input validation is achieved by reconciling agents' behavioural equations with empirical regularities. Output validation follows a two-step procedure where the models' abilities to reproduce historical stylised facts is considered first and followed by an evaluation of how closely they sketch the dynamic behaviour of key aggregate variables (e.g. GDP, emissions, energy demand, etc.). Extensive sensitivity and uncertainty analysis of parameters is carried out, with particular attention to the climate side of the models.

5.4. Model runs, outputs and usage

Once established, the new European model will be used to explore and assess adaptive pathways towards stakeholder-defined visions of future land system characteristics. Using the inputs set out above, each potential pathway (including scenario-specific climatic and socio-economic changes, and pathway-specific institutional effects) will be simulated in theoretical and empirical (European) settings to:

(a) investigate the theoretical effects of specific forms of land manager and institutional behaviour within the pathways (exploring basic potential behavioural impacts on pathways);
(b) investigate the theoretical effects of different adaptation options and their sensitivity to simulated behavior;
(c) simulate pathways as closely as possible to assess their ability to reach the visions.

This work will also provide systematic information on different adaptation options to the rIAM, through look-up tables of key characteristics such as speed, scale and spatial properties of adaptive processes. It is also expected that tipping points in the socio-economic systems modelled will be identified through the links with the WP5 ABMs.

Simulation results will be produced across a range of spatial and temporal resolutions from 1km^2 to national/European spatial scales and from annual to decadal temporal scales. Key results will be land use types and associated land cover (and related aggregate metrics such as extent and connectivity), production levels of ecosystem services, final levels of productive capitals, institutional actions and their efficacy, and agreement in these and other terms with the visions. All results will be related to their scenario and pathway contexts and specific effects of these contexts identified. Together, these will provide an assessment of the potential development of the European land system that is complementary to that produced by the rIAM.

6. Conclusions and timetable

This report has outlined the specification for model improvement and development within the European case study of IMPRESSIONS. The specification will support the delivery of the objective for WP3B of advancing and applying European scale methods and models to better quantify and understand impacts, risks, vulnerabilities and adaptation options associated with a range of scenarios for key economic, social and environmental sectors and their cross-sectoral interactions. The specification will: (a) allow the modelling framework to extend to 2100 to take account of long-term projections of climate and socio-economic change; (b) enable the incorporation of quantified model inputs derived from the RCPs and SSPs (from WP2); and (c) facilitate further development of a range of modelling approaches (emulators; process-based; agent-based models) to provide better representation of dynamic time- and path-dependent impacts, adaptation and vulnerabilities.

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