



Global Scale Application of Climate Change Impact, Adaptation and Vulnerability (CCIAV) models

Deliverable D3A.1

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Preface

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

This report describes the modelling of impacts, adaptation and vulnerability (CCIIV) conducted using global scale models using climate and socio-economic scenarios developed in Work Package (WP) 2 of the project. Much of the information received and many of the decisions taken that are reflected in this document were obtained at three modelling workshops held in London (April 2014), Pisa (September/October 2014) and Copenhagen (December 2015) as well as at General Assembly sessions in Oxford (January 2014), Barcelona (January 2015) and Florence (January 2016). These meetings were attended by representatives of all partner and other affiliated organisations working with global models, to which the authors express their great appreciation. Some specific global model runs were also carried out ahead of a stakeholder workshop for the Central Asia (EUx) case study in Baku (May 2016).

Summary

This deliverable describes the modelling of impacts, adaptation and vulnerability (CCIIV) conducted using global, spatially-explicit sectoral and integrated assessment models. Simulations have been undertaken for testing model sensitivity and examining model behaviour, as well as for exploring responses under climate and socio-economic scenarios developed in Work Package 2 of the IMPRESSIONS project. The suite of global model employed in the project consists of two global integrated assessment models (IMAGE and iPETS), three sectoral models (AIM/Impact [Health], M-GAEZ and VISIT) that are associated with a third integrated assessment model (AIM), a global biodiversity model (GLOBIO3) and a global integrated water model (WaterGAP). These models are being used: (i) to define boundary conditions for model simulations at the European scale; (ii) to quantify impacts under the selected climate and socio-economic scenarios in regions outside Europe; (iii) in a sensitivity analysis of responses to systematic changes of selected climate and socio-economic variables; (iv) to quantify impacts in a study area in Central Asia which subsequently helps to gain insights on the implications of indirect impacts of climate change for the European Union; (v) to quantify the effects of European adaptation strategies on other regions in the world; and (vi) to compare to simulation results of models operating at finer scales. Results from some of these analyses are reported here, while others planned for a later stage of the project are outlined and will be reported in detail in D3.2 (due December 2017).

1. Introduction

1.1. Description of work

The description of work (DoW) refers to Task 3A.1 as contributing to this deliverable, namely “[carrying] out simulations of future sectoral and economy-wide impacts under RCP/SSP-based scenarios (linked to WP2) using global, spatially-explicit sectoral and integrated assessment models (IAMs)”. The global models that have been applied are as follows (Table 1):

- Sectoral impact models that have been developed for incorporation in the Asia-Pacific Integrated Model (AIM);
- IMAGE, a global integrated assessment model;
- iPETS, a global, multi-regional IAM that uses the CLM (Community Land Model) as its physical land surface model;
- GLOBIO, a global biodiversity model;
- WaterGAP, a global integrated water model.

An additional global-scale human health model on labour productivity, is currently being developed in the project and may also be used in some of the global model applications outlined in this report.

Table 1: Overview of global model applications in IMPRESSIONS. An X denotes an ongoing or planned model application and numbers in the top row are sections of this report.

Global model	Appendix Model description	2 Boundary conditions	3.1 Impacts	3.2 Sensitivity	4 Indirect impacts	5 Adaptation strategies	6 Model comparison
AIM/Impact [Health]	A1.1		X	X	X		X
M-GAEZ	A1.2		X	X	X	X	X
VISIT	A1.3		X	X	X		
GLOBIO	A1.4		X	X	X	X	
WaterGAP	A1.5		X	X	X	X	X
iPETS	A1.6				X		X
IMAGE	A1.7	X	X			X	

In the DoW, research with these models was seen as serving five distinct purposes in the IMPRESSIONS project, providing:

- Quantitative estimates of global developments under high-end scenarios to be used as boundary conditions for continental and regional/local climate change impacts, adaptation and vulnerability (CCIAV) modelling in the IMPRESSIONS case study regions studied in WPs 3B and 3C;
- Estimates of impacts, sensitivities and risks across different world regions, along with their uncertainties, based on scenario analysis and the use of impact response surfaces;
- Estimates contributing to Task 3A.2, for assessing the implications for Europe of indirect impacts of climate change occurring in other parts of the world;
- Estimates of the consequences of European adaptation strategies for the rest of the world;
- Impact estimates for comparison with results from finer-scale models in Europe (as described in Task 3.4).

Sections 2 to 6 report the status of global modelling activity in addressing these five themes and plans for future work during the remaining months of the IMPRESSIONS project. An overview is provided in Table 1 and brief descriptions of each model are included in Appendix 1.

1.2. Links to other work packages

Global model simulations have been applied primarily in analyses based on climate and socio-economic scenarios developed in WP2. To date, results for the European and Central Asian regions have been the main focus of interest, providing inputs to the IMPRESSIONS regional case studies reported elsewhere in WP3. Links to WPs 4 and 5, including simulations for defining pathways of adaptive actions towards stakeholder-defined future visions, are at the planning stage in anticipation for the third series of stakeholder workshops that will take place in 2017.

2. Using global models to define boundary conditions for impact modelling

Climate change impact, adaptation and vulnerability (CCIIV) models are applied at three geographical scales in the IMPRESSIONS case studies: global, European and regional (sub-national for Hungary and Scotland, and transnational in the Iberian Peninsula and Central Asia). All models are being run for future conditions characterised using climate and socio-economic scenarios (Figure 1).

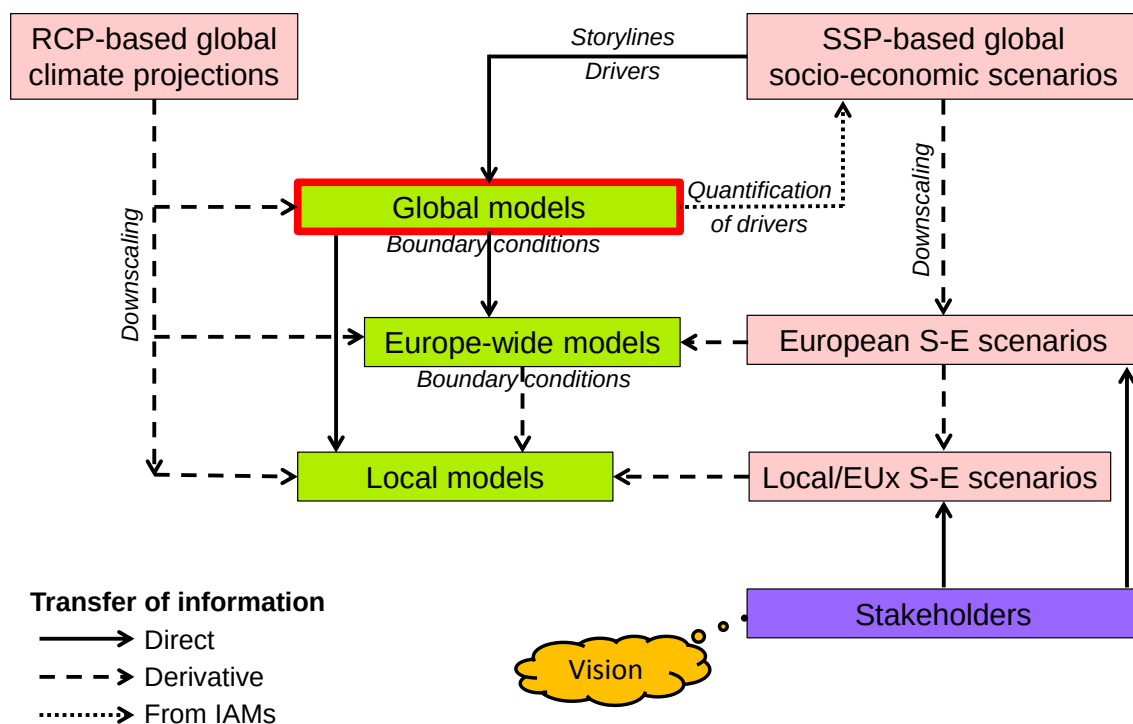


Figure 1: The role of global models in the possible transfer of information between models, scenarios and stakeholders in IMPRESSIONS (S-E: socio-economic; IAM: integrated assessment model; RCP: representative concentration pathway; SSP: shared socio-economic pathway; EUx: Central Asia case study external to EU).

The construction of scenarios in IMPRESSIONS is described in Deliverables D2.1 (Kok et al., 2015), D2.2 (Kok & Pedde, 2016) and D2.3 (Madsen et al., 2016) and is based on a global scenarios framework of Representative Concentration Pathways (RCPs) and Shared Socio-economic Pathways (SSPs). Global integrated assessment models (IAMs) are used to quantify some of the key driving variables defined

for the global scenarios (dotted arrows in Figure 1). Some of the key quantitative demographic and economic input variables for CCI/V models are already specified for the case study regions in the global scenarios. Other regional variables have been specified through stakeholder discussions. However, in some cases, models operating at European and regional scales require information on developments at the global scale that are consistent with a particular scenario being examined but were not provided in the scenarios.

Global models can provide data on these exogenous boundary conditions, either directly at the scale of interest, or derived via a model operating at an intermediate scale (Figure 1). In IMPRESSIONS the variables required as input to different models were identified based on a modellers' questionnaire and specified through the development of data dictionaries as described in Deliverable D3.1 (Carter et al., 2015). At the time of writing, only a few global scale variables have been requested from global models. Suitability checking of output variables to conform to the input needs of several models being applied at the European scale is currently underway (Table 2). In all cases, following a project decision to encourage a consistent approach to the selection of variables, these have been taken from the IMAGE integrated assessment model (van Vuuren et al., 2011).

Table 2: Global scale exogenous input variables (boundary conditions) for IMPRESSIONS models obtained from global models. Based on Table 4.1 in Carter et al. (2015).

European model	Variable	Global model input source details
CRAFTY 1.0	Demand for land use goods/services	IMAGE agriculture, food and forestry demand (consistency still being evaluated)
IAP2	Change in crop prices	IMAGE crop price (consistency still being evaluated)
IAP2	Policy pressure to increase bioenergy crop production	IMAGE indicator for primary energy: Biomass (consistency still being evaluated)
Heat-related mortality	Indicator of socio-economic conditions	IMAGE Human Development Index (under consideration)
WaterGAP meta-model	Thermal electricity production	IMAGE coal, oil and nuclear electricity production (consistency still being evaluated)

3. Using global models to explore impacts and sensitivities

Global models are being applied in IMPRESSIONS to explore impacts in various sectors both under scenarios of climate and socio-economic change and in systematic sensitivity analyses using impact response surfaces. Available and planned simulations are detailed in Table 3. Progress in both of these activities is summarised for each model in the following sub-sections.

3.1. Scenario-based impacts from global models

Simulations with global impact models assuming future climate and socio-economic conditions defined within a global scenarios framework of RCPs and SSPs are being investigated in IMPRESSIONS. Some simulations have been conducted or are planned using models applied by project partners or members of the IMPRESSIONS external expert panel. Other simulations are from global models that have been applied outside the project but which offer potentially valuable results for use within IMPRESSIONS. Available and planned scenario-based simulations are summarised in Table 3.

Table 3: Available or planned scenario-based simulations using global impact models in IMPRESSIONS.

Model	RCP x SSP, GCM	Application in IMPRESSIONS
IMAGE/ GLOBIO3	SSP1/SSP3, internal climate model	- Boundary conditions (see section 2) - EUx case study (see section 4.1) - Scale comparison (see section 6)
i-PETS	SSP3+5/RCP8.5+4.5	- Scale comparison (see section 6) - Population projections for Central Asia
AIM impact models	{ SSP1/SSP3 } x { RCP2.6/4.5/6.0/8.5 }, selected GCMs	- EUx case study (see section 4.1) - Scale comparison (see section 6)
Labour productivity	ISI-MIP GCMs, IMAGE SSP1+SSP3	- Global application
WaterGAP	Hydrology: RCP2.6/4.5/6.0/8.5 Water use: projections of socio-economic drivers developed for EUx (see section 4)	- EUx case study (see section 4.1) - Scale comparison (see section 6)
ISI-MIP	RCP2.6/4.5/6.0/8.5, 5 GCMs	- EUx case study (see section 4.1)

Two examples of model simulations previously conducted under high-end scenarios are provided below from selected models. Additional examples for scenarios specifically adopted in IMPRESSIONS are presented in section 4, for Central Asia, with other runs in preparation.

3.1.1. Example 1: GLOBIO3 estimates of mean species abundance under high-end scenarios

The GLOBIO3 model is a tool to assess past, present and future impacts of human activities on biodiversity (see Appendix A1.4). Since 2005 the GLOBIO3 model has been extensively used for integrated, global and regional environmental assessments. These assessment reports aim to evaluate scenarios and policies targeting the reduction of biodiversity loss. Two reports where the GLOBIO3 model analysed the consequences of alternative (high-end) scenarios for terrestrial biodiversity are: (i) the Global Environmental Outlook 4 (GEO-4); and (ii) the Global Deserts Outlook.

Findings in the GEO-4 report (UNEP, 2007) show that *Markets First* is the scenario with the highest decrease in mean species abundance. The *Markets First* scenario (SRES A1F1) is analogous to SSP5/RCP8.5 used in IMPRESSIONS. The scenario applied in the GEO-4 report depicts a global mean surface temperature increase of about 2.2°C in 2050. Africa, Latin America and the Caribbean experience the greatest losses of terrestrial biodiversity by 2050 in *Markets First*, where mean species abundance decreases by 25% and more in those regions (UNEP, 2007).

Although the scenario SRES A2 analysed in the Global Deserts Outlook (UNEP, 2006) cannot be considered as a worst-case situation, it is the scenario closest to historic trends in development with regard to land degradation and subsequent impacts on biodiversity and human livelihoods. Therefore, the results provided in term of mean species abundance follow such development trends. The most notable impact observed when using the SRES A2 scenario is perhaps that the rate of biodiversity loss in deserts may as much as double in the coming decades. The SRES A2 projects a further decline in mean original species abundance from about 65% in deserts in 2000 to a mean of 62.8% by 2030 (range 60–65 %) and 58.3% by 2050 (range 53–62 %). Figure 2 shows species abundance in deserts for 2000 and 2050.

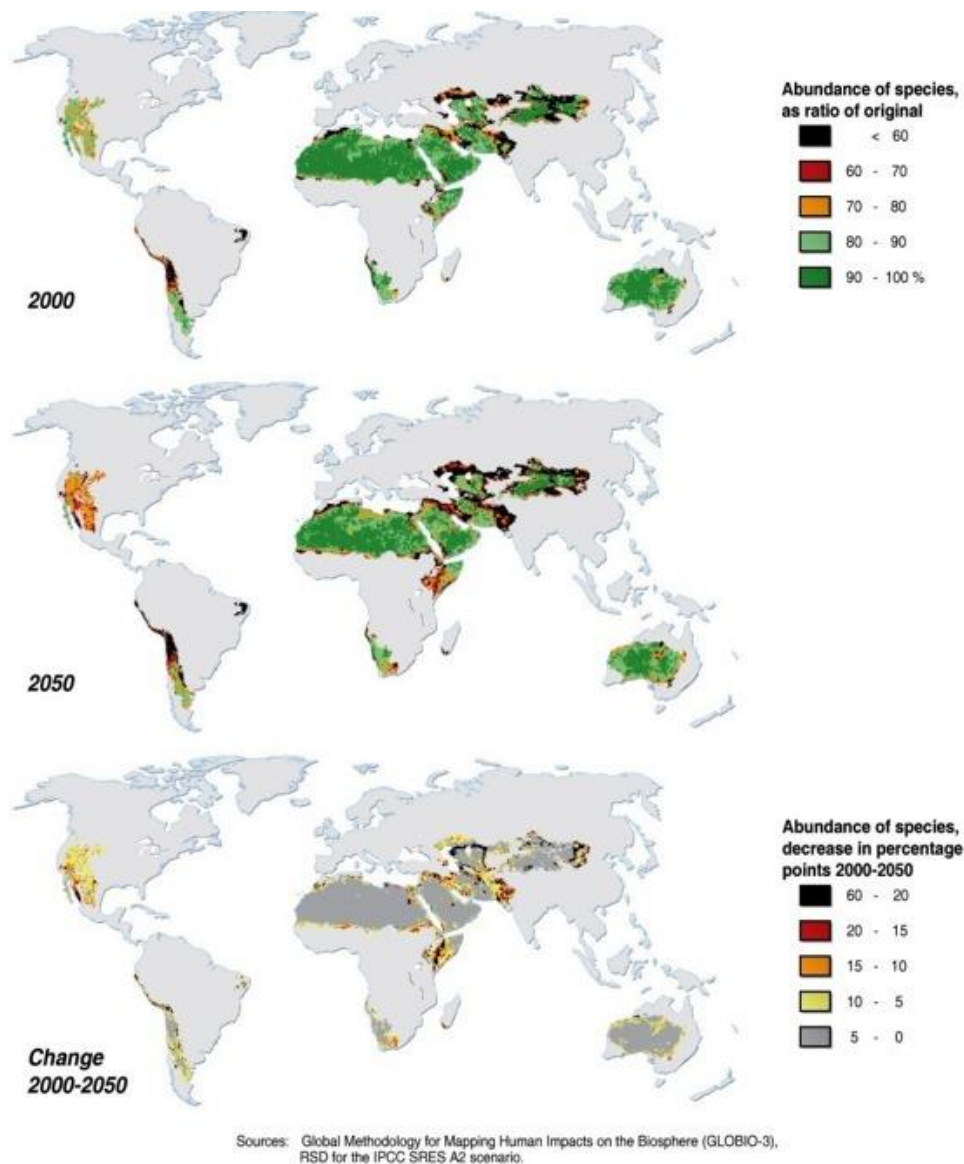


Figure 2: Relative biodiversity scenarios for deserts 2000-2050 under the SRES A2 scenario. Source: Global Deserts Outlook (UNEP, 2006).

Desert areas are relatively pristine and have seen little changes induced by human activities, therefore the relative species abundance is high. Impacts are most clearly seen at the edges of deserts, in the basins of western North America, along Baja California, and in the drylands of Central Asia (an IMPRESSIONS case study region) and the inland Far East.

3.1.2. Example 2: WaterGAP estimates of future water resources

The WaterGAP model is a tool for computing indicators of water use and water availability on a global grid or on a river basin level. Here we report simulations of WaterGAP2, the coarser resolution version of the model described in Appendix A1.5. Results on mean annual discharge were used in a multi-model assessment of climate change impacts on water resources driven by RCP8.5 climate projections (Schewe et al., 2013). In the study, an ensemble of five GCMs and nine global hydrological models was applied to investigate the uncertainty of modelling future water resources under high-end climate

change. The human dimension of future change in river discharge was assessed by reconciling the results with the spatial distribution of population according to SSP2 projections.

The model inter-comparison revealed large uncertainties of future water resources estimates introduced by GCM output and global hydrological models. The uncertainty due to hydrological models was particularly large in regions with decreasing water resources. Within the ensemble of global hydrological models, WaterGAP2 turned out to be rather robust with results close to the ensemble average in most of the cases.

Under high-end scenarios, the share of global land area and population confronted with severe water scarcity is likely to grow considerably. The dominant drivers of water stress are increasing water withdrawals, in particular in the domestic sector, due to population growth and higher water use intensities stimulated by increasing incomes. Nevertheless, climate change is projected to aggravate water stress due to a reduction of water availability.

3.1.3. Example 3: M-GAEZ simulations for adaptation of wheat production

M-GAEZ is a global crop yield model that can be applied to a range of different crops (see Appendix A1.2). In this example, the model has been used to simulate wheat yields under changing climate conditions based on an ensemble of nine climate model projections for RCP8.5 forcing. As climate changes, for each ten year time interval, different adaptation measures are also simulated involving expanding irrigation infrastructure and switching crops to more heat tolerant varieties. Adaptation pathways are identified for each country that provide the minimum adaptation required to maintain yields at their current levels under changing climate throughout the 21st century. The effect of not implementing this adaptation at each time step was then evaluated and compared with the timely introduction of adaptation at different lag times, assuming that climate forecasts are being acted upon.

Figure 3 shows how the negative impacts of climate change could be moderated by implementing adaptations steadily, based on anticipated changed conditions, compared to situations where adaptation is not implemented or is poorly timed.

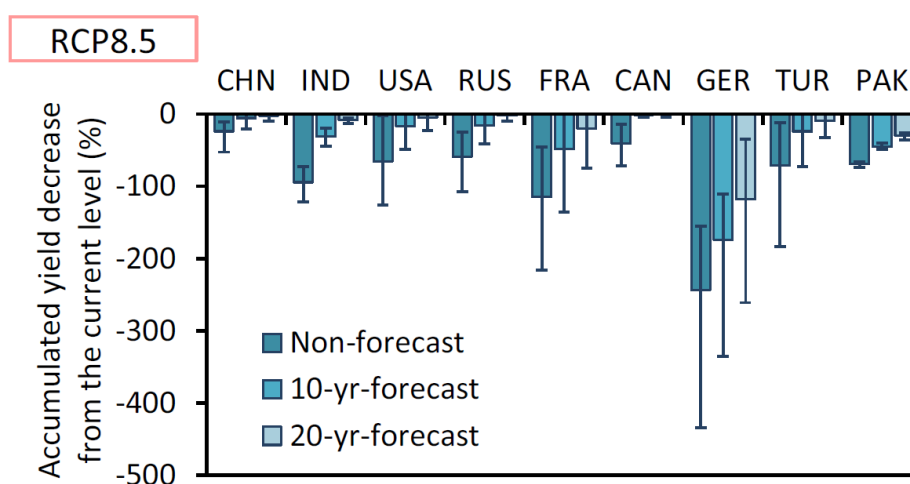


Figure 3: Model simulations with M-GAEZ showing the relative effectiveness of adaptation of wheat management to maintain current yield levels for different assumptions about climate prediction lead-time under an ensemble of RCP8.5 climate projections in nine sample countries. Source: Tanaka et al. (2015).

3.2. Sensitivity analysis with global models using impact response surfaces (Phase 1)

A number of global models have also been applied in sensitivity studies applying the impact response surface (IRS) approach. More details can be found in Deliverable D3.1 (Carter et al., 2015) who summarise the approach as follows: “An IRS is a graphical device for plotting the modelled behaviour of an impact variable in response to changes in two key explanatory variables that span the x- and y-axes of the plot. A key benefit of the IRS method is that it is a systematic way of analysing the sensitivities of an impact model to changes in the variables being tested and provides impact estimates across a wide range of conditions.”

A protocol was provided to modellers for a two-variable sensitivity analysis of an impact model, the results of which can be plotted as an IRS (see Annex B in Carter et al. 2015). Two phases of analysis were defined: a basic method (Phase 1) and a combined method (Phase 2). So far, simulations with global models have been conducted for Phase 1, which is the basic method with simplifying assumptions (e.g. no seasonal cycle in change in climate variables). Results from these simulations are summarised here and will be reported in more detail in the IMPRESSIONS Special Issue of Regional Environmental Change (Fronzek et al., in prep.).

Details of the variables tested and regions of application of global models under the Phase 1 IRS study are presented in Table 4. Although, by definition, results from global models are available worldwide, for purposes of comparison they have been extracted in all cases here for geographical domains over Europe. In the following sub-sections we summarise the results received to date.

Table 4: Global models applied in the IRS sensitivity analysis, driving variables to be tested and focal regions for which results are presented.

Model	X	Y	Focal region
AIM/Impact[Health]	Temperature	Population	Europe
M-GAEZ	Temperature	Precipitation	Europe
VISIT	Temperature	Precipitation	Europe
GLOBIO	Temperature	Land use	Europe
WaterGAP meta model	Temperature	Precipitation	Europe

3.2.1. Sensitivity of heat stress mortality to temperature and population from AIM/Health

AIM/Health estimates excess mortality due to heat stress for each grid cell based on daily maximum temperature and population density (see Appendix A1.1). For the IMPRESSIONS IRS study, the model version described in Honda et al. (2014) was used. Furthermore, daily maximum temperature based on NCEP/DOE AMIP-II Reanalysis Model from 1981 to 2010 and death number density provided by WHO for 2008 were used as baseline period input data. As the driving variable X, daily maximum temperature was additively perturbed for the range between -1°C and +11°C with the interval of 1°C (for perturbations $\leq 5^\circ\text{C}$) or 2°C ($> 5^\circ\text{C}$), while population density (death number density) was multiplicatively perturbed for the range between -90% and +210% with the interval of 30% as the driving variable Y. Change in population structure was not considered.

Regarding the sensitivity to the change in population, since change in population structure is not considered, excess mortality due to heat stress increases in proportion to the increase in population. For the sensitivity to the change in temperature, it is higher in the British Isles and Mediterranean than in other regions and increases by more than 300% for a 4°C temperature increase from the baseline period (Figure 4).

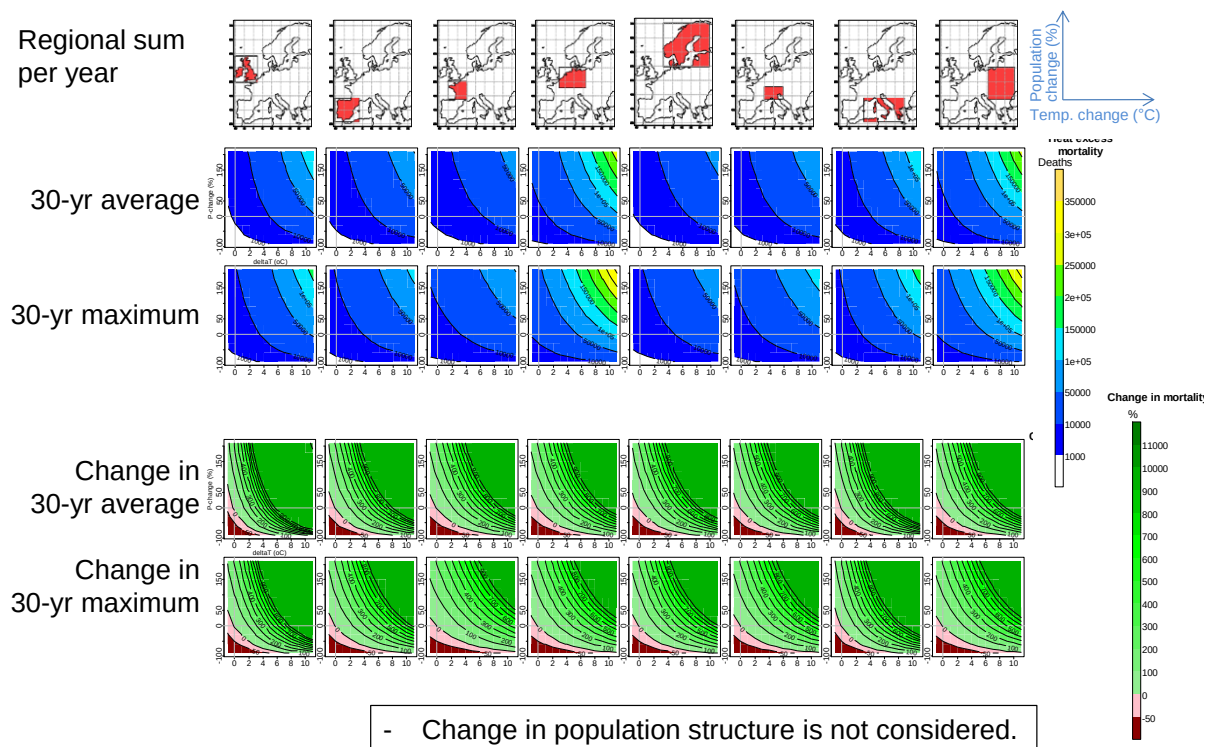


Figure 4: Results over European sub-regions from the heat stress mortality model.

3.2.2. Sensitivity of crop yield to temperature and precipitation from M-GAEZ

M-GAEZ is described in Appendix A1.2. IRSs for seven crops (maize, wheat, wetland rice, barley, white potato, sugar beet and soybean) were developed, while temperature and precipitation were chosen as the driving variables X and Y, respectively. Monthly climatology CRU-TS2.1 for the period from 1981-2000 was chosen as baseline input data. Monthly mean temperature was additively perturbed for the range between -1°C and $+11^{\circ}\text{C}$ with an interval of 1°C (for perturbations $\leq 5^{\circ}\text{C}$) or 2°C ($> 5^{\circ}\text{C}$) as the driving variable X, while monthly precipitation was multiplicatively perturbed for the range between -60% and $+40\%$ with a step of 10% as the driving variable Y. The CO_2 fertilization effect was not considered, while some adaptation measures were considered (optimal variety and planting date is chosen both under the baseline and perturbed climate conditions). For spatial aggregation, estimated potential crop productivity was averaged without being weighted by present cultivated area.

Sensitivity of crop productivity to the two driving variables (temperature and precipitation) is quite non-linear and heterogeneous among the regions. For example, with a modest increase in temperature ($< 3^{\circ}\text{C}$) and no change in precipitation, wheat productivity will increase in the Iberian Peninsula, France, northeast Europe and the Mediterranean (green shading) and decrease in the British Isles, central Europe and eastern Europe (red shading). Responses of crop productivity are more complex when considering combinations of temperature and precipitation change (Figure 5).

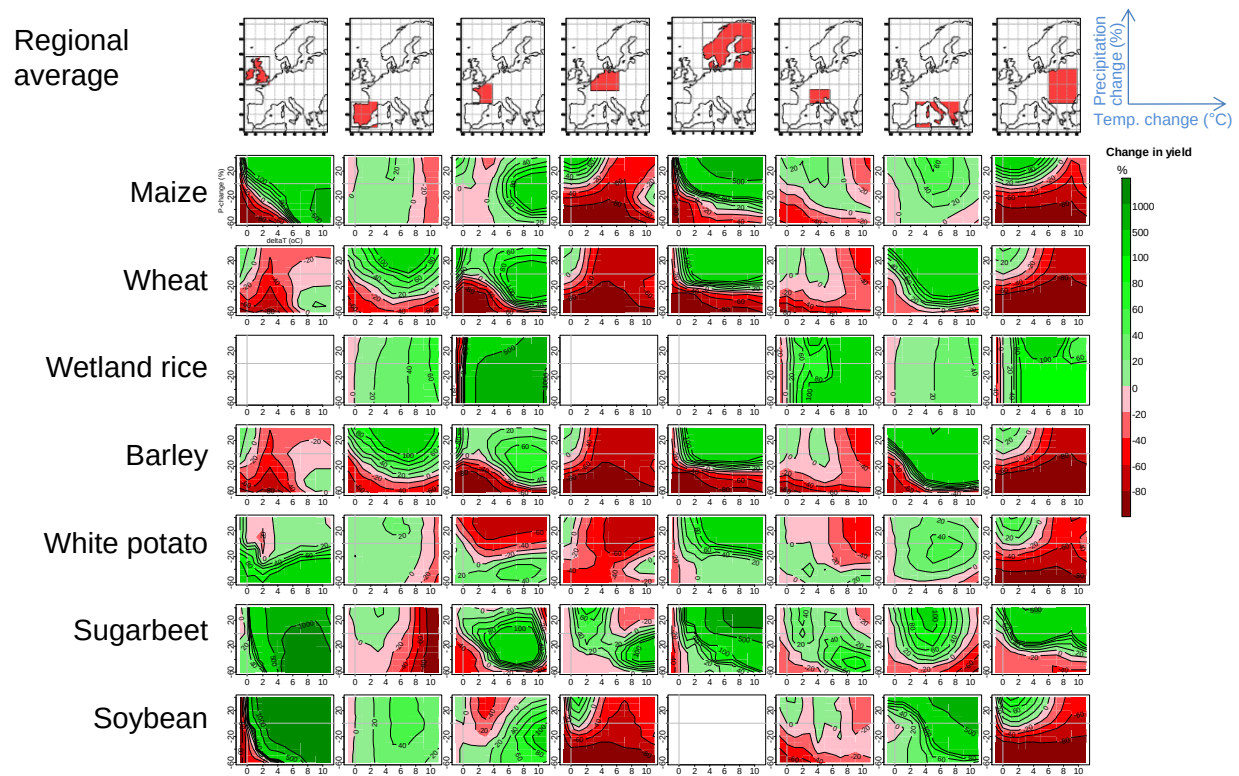


Figure 5: Results over European sub-regions from the M-GAEZ crop yield models.

3.2.3. Sensitivity of net primary production to temperature and precipitation from VISIT

The VISIT model (Appendix A1.3) has been used in the IRS study to simulate the sensitivity of net primary production (NPP) to temperature and precipitation (chosen as the driving variables X and Y, respectively). The monthly CRU-TS3.23 climatology for the period from 1981 to 2000 was chosen as baseline input data. Monthly mean temperature was perturbed additively for a range between -1°C and $+11^{\circ}\text{C}$ with an interval of 1°C (for perturbations $\leq 5^{\circ}\text{C}$) or 2°C ($> 5^{\circ}\text{C}$) as the driving variable X, while monthly precipitation was perturbed multiplicatively for the range between -60% and $+40\%$ with a step of 10% as the driving variable Y. CO_2 fertilization was not considered.

In all the sub-regions examined, NPP increased (decreased) with an increase (decrease) in precipitation, as a result of reduced water stress (Figure 6). While NPP decreased with a decline in temperature, responses to a slight increase in temperature were different among the sub-regions. With a large increase in temperature, NPP declined in all regions, due to heat stress effects on photosynthetic production. It should be noted that NPP is very sensitive to the change in atmospheric CO_2 concentration (CO_2 fertilization effect, typically $+30\%$ per CO_2 doubling), which was assumed constant in this exercise.

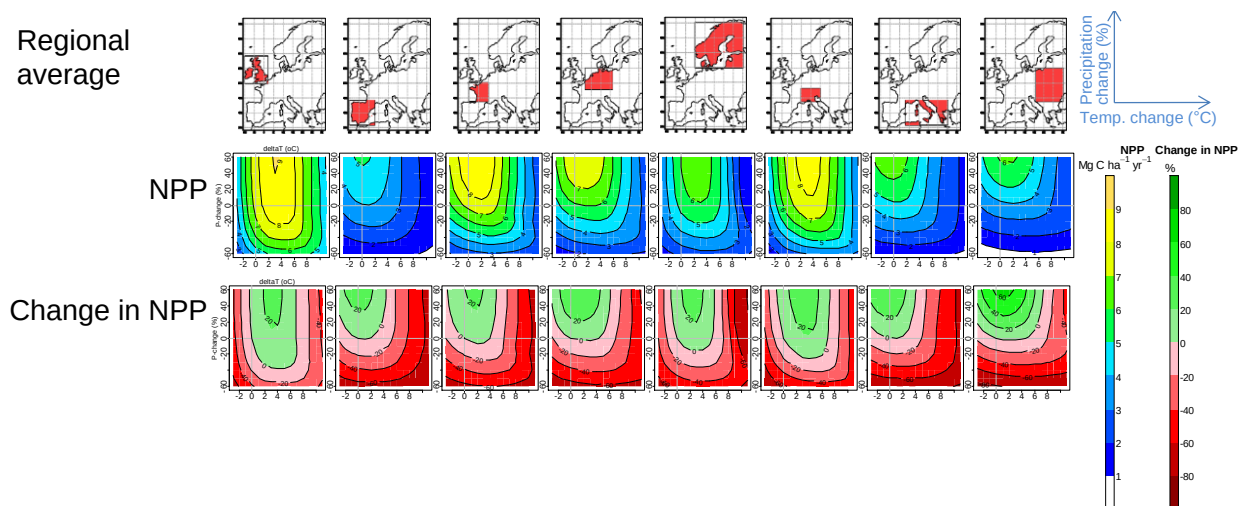


Figure 6: Results for Net Primary Production over European sub-regions from the VISIT model.

3.2.4. Sensitivity of terrestrial biodiversity loss to temperature and land use from GLOBIO

A sensitivity analysis was conducted with GLOBIO (see Appendix A1.4) to determine the response level of mean species abundance (MSA) to changes in two explanatory variables: global mean temperature (GMT) and cropland change. A total of 117 combinations were used to perform the model runs in GLOBIO. The baseline year selected for the analysis is 2010. The variable GMT is derived from the IMAGE model, and values were perturbed between -1°C and 11°C at intervals of 1°C . The variable cropland change was perturbed between -10% and $+30\%$ at intervals of 5% relative to the baseline year. The input data used in the sensitivity analysis correspond to revised data from the baseline scenario used in the Global Biodiversity Outlook 4 (GBO-4), a periodic report summarizing the latest status and trends of biodiversity. The results were aggregated to eight European sub-regions by averaging the values of all grid cells in a region (Figure 7).

Results show that MSA decreases with increasing GMT and increasing cropland. Firstly, the effects of climate change are quantified for each biome separately implying that the degree of biodiversity loss in each sub-region is strongly linked to the terrestrial biome located in the region. For example, the Mediterranean sub-region experiences a dramatic decrease of MSA, if GMT change is high (MSA=0.147 at GMT change of $+11$ degrees). In other words, the Mediterranean forest biome is highly vulnerable to increasing global mean temperature.

Secondly, an increase in cropland implies a decrease in natural vegetation classes; the sub-regions have different vegetation classes and land use patterns. GLOBIO first allocates cropland on non-forest natural vegetation classes followed by forest classes. For example, the sub-regions eastern Europe and France are characterised by large crop areas and are likely to experience larger effects from changes in cropland. The sub-regions Alps, British Isles and northeast Europe are characterised by having large portions of natural vegetation classes (i.e. forests), and increases in cropland have a lesser effect in these regions.

Results displayed in the IRS plots are representative for each sub-region. Climate change and land use change are two of the major drivers of biodiversity loss and the MSA in each sub-region indicates a plausible situation under the selected conditions. Because GLOBIO is a linear model, there are no thresholds in the results. MSA and changes in MSA relative to the unperturbed baseline values (i.e.

the simulations without changes in temperature and cropland) over the eight European sub-regions are shown in Figure 7 and Figure 8.

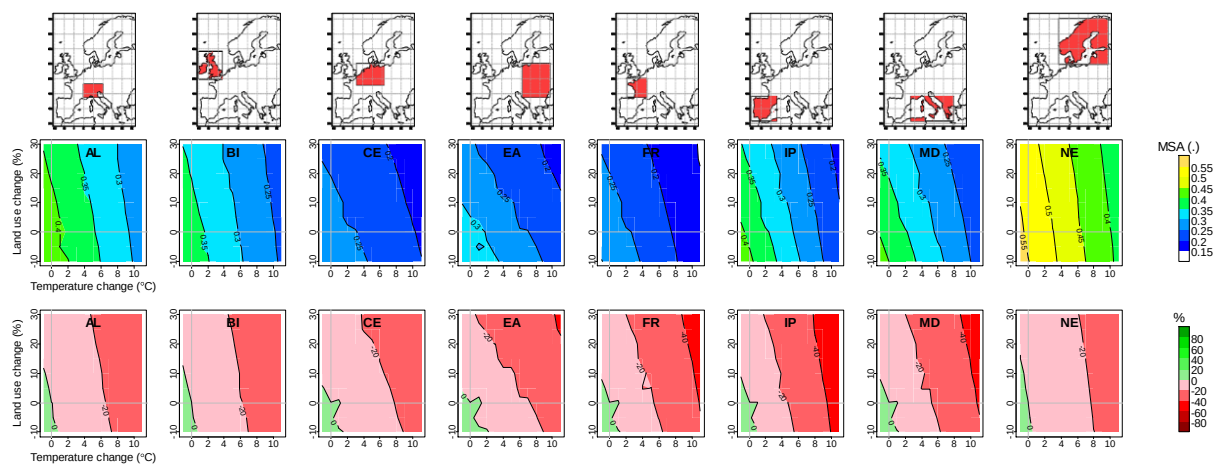


Figure 7: Results over European sub-regions for mean species abundance (MSA, top row) and change in MSA relative to the baseline value (bottom row) simulated with the GLOBIO model.

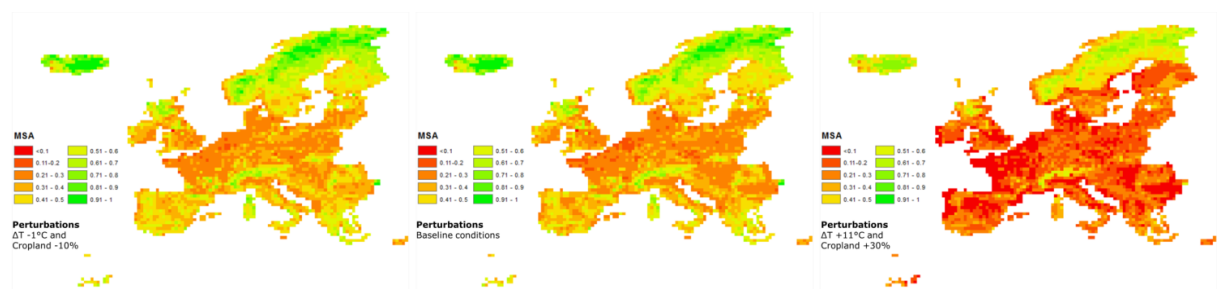


Figure 8: Maps for mean species abundance (MSA) under different simulations: -1°C and -10% cropland (left panel); baseline conditions (middle panel); +11°C and +30% cropland (right panel).

This sensitivity analysis exercise is a first step to understand how the GLOBIO model behaves under such extreme conditions. An increase of 7°C or more in GMT is far outside the valid range of the GLOBIO model. Projections for the year 2300 may show this temperature increase in RCP8.5, and hence are highly uncertain. GLOBIO shows a fairly linear response to climate change and land use change, a consequence of the lack of interactions within the model.

3.2.5. Sensitivity of river discharge to temperature and precipitation from WaterGAP3

The global hydrology and water use model WaterGAP is described in Appendix A1.5. In this sensitivity analysis, the hydrological model has been run with climate input data for the period 1981-2010 (WFDEI, Weedon et al., 2014). WaterGAP was run with a 10-year spin-up (“1971-1980”) and simulation results for 1981-2010 were used for plotting impact response surfaces. The climate input was systematically adjusted to model multiplicative changes in precipitation ranging between -60% and +40% with a step of 10%, and additive changes in temperature ranging from -1°C and +11°C with an interval of 1°C (for perturbations $\leq 5^\circ\text{C}$) or 2°C ($> 5^\circ\text{C}$), evenly applied to each daily value in each grid cell. Hence, the results of a total of 110 model runs were used to build IRSs relating relative change in several statistics of river discharge at selected river outlets to changes in mean annual temperature

and annual precipitation. Selected statistics of river discharge were average annual river discharge, low-flow river discharge (discharge exceeded in 95% of the days in a year), high-flow river discharge (discharge exceeded in 5% of the days) and flood-flow discharge, defined as the median annual maximum discharge.

The results were aggregated for eight European regions with the mean value of the flow parameter of interest at all outlet cells in a region used to characterize the region. Results are shown in Figure 9. Note that the representative outlet may differ among flow parameters.

In general, the IRSs are rather smooth with river flow being more sensitive to precipitation (++) than to temperature (-) change. However, a few combinations of region and parameter stand out from this general picture. For low flows in northern Europe, a relative maximum of discharge as a function temperature at any constant precipitation change can be observed in the range of +2 to +4 °C warming. For instance, at zero change in precipitation, low flow decreases for decreasing temperature and increases for increasing temperature. Low flows reach a maximum at around +4 °C warming and start to decline with temperature increase beyond that. In addition to enhanced evaporation, increasing temperature has two opposing effects: (i) enhanced snow melt provided a snow cover exists; and (ii) reduced snow accumulation. In the range from -1°C to 2-4°C, the existing snow cover melts faster with increasing temperature leading to increasing low flow discharge. If temperature increases by more than 2-4 °C, snow accumulation is diminishing and the relationship of low flow discharge and temperature is dominated by increasing evaporation at higher temperatures. A similar effect can be observed in the Alpine region and eastern Europe.

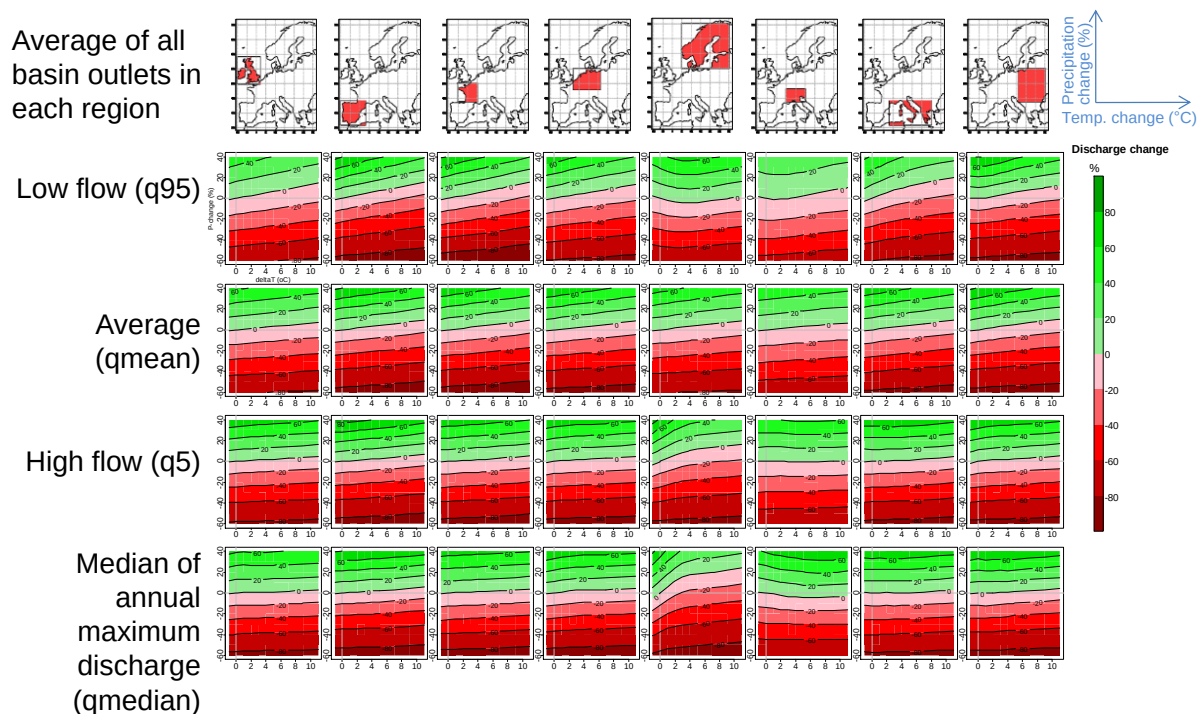


Figure 9: Results over European sub-regions for river discharge from the WaterGAP3 model (average of all basin outlets per sub-region).

In contrast, high flow and flood flow discharge in northern Europe is predominantly affected by the reduction of snow accumulation due to increasing temperature. As high flows and flood flows often coincide with strong snow melt, discharge peaks are limited by the volume of water stored in the snow cover. In the Alpine region, temperature increase tends to increase flood flow discharge. The limiting

effect of water storage in the snow cover due to reduced snow accumulation is less dominant than in northern Europe. During the typical weather situation leading to flood flows, enhanced snow melt, which may also affect a larger elevation range, has a positive effect on discharge.

3.3. Impact risk analysis with global models using impact response surfaces (Phase 2)

Phase 2 is a further application of the IRS method, adding elements to the basic method that improve the realism of the model simulations and combining the resulting IRSs with probabilistic projections for the same two variables. This combined method will enable estimates to be made of the likelihood of a certain specified impact occurring, so that impacts can be assessed within a quantified risk framework. A protocol for the Phase 2 combined method is under development, and IMPRESSIONS global modelling groups will be invited to participate in this during 2017.

4. Using global models for assessing the implications for Europe of indirect impacts of climate change occurring in other parts of the world

Global models are the only tools available in IMPRESSIONS to quantify potential impacts of scenario-based climate and socio-economic changes occurring in regions outside Europe. Most models do this independently by sector and over a regular network of grid boxes, globally. A few integrated models can also estimate the repercussions of regional impacts for the global economy (e.g. through commodity prices, employment or trade), hence providing useful results for considering the implications for Europe of impacts occurring outside Europe (labelled “indirect impacts” in the IMPRESSIONS project).

4.1. Global impact models applied in the Central Asia (EUx) case study

To date, the use of global model simulations to inform discussions of “indirect impacts” of climate change for Europe has focused on impacts in the five Central Asian republics of Kazakhstan, Kyrgyzstan, Tajikistan, Turkmenistan and Uzbekistan (Figure 10). The Central Asian case study in IMPRESSIONS is referred to as EU external or EUx.

Where feasible, model runs were carried out for the IMPRESSIONS RCP/SSP scenario combinations (Table 5). The models that have been applied especially for the EUx case study are listed in Table 6.

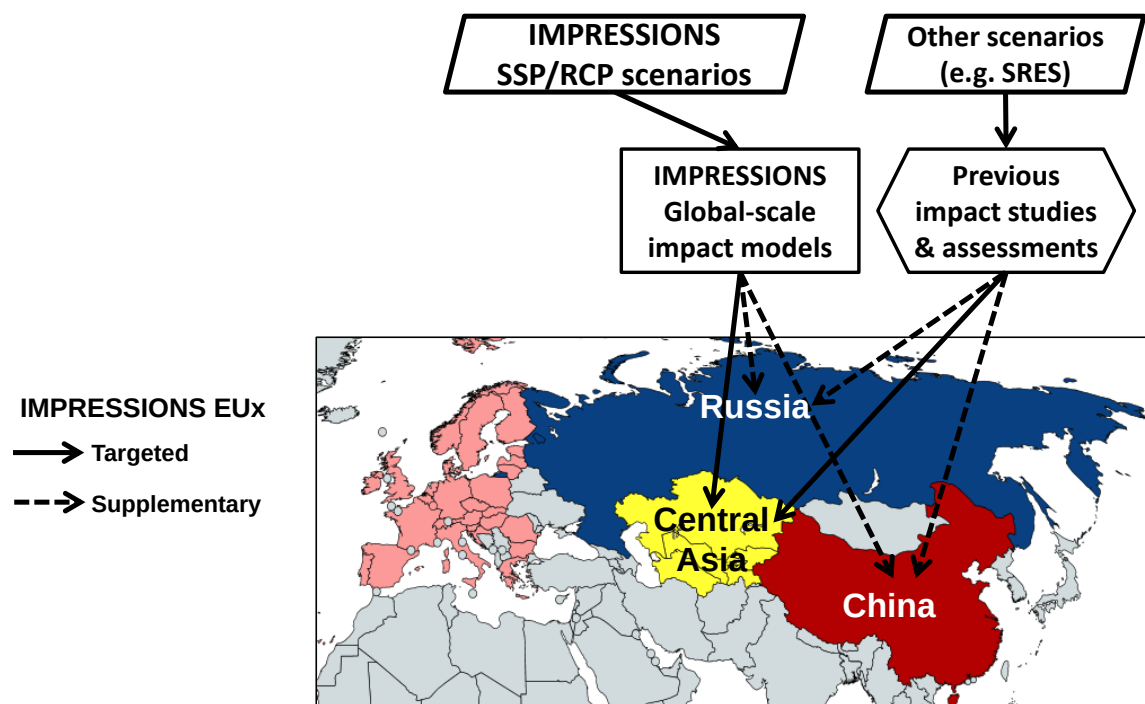


Figure 10: The use of global model outputs to explore implications for Europe of climate change impacts on the Central Asian region and its neighbours (EUx case study).

Table 5: IMPRESSIONS socio-economic and climate scenario combinations for the period to 2100 applied in the EUx case study of Central Asia. See Deliverable D2.2 (Kok & Pedde, 2016) for further details of the socio-economic scenarios developed for Central Asia.

Socioeconomic (SSP)	+ Climate (RCP)
SSP3 Regional rivalry	+ RCP8.5 (high-end)
SSP5 Fossil-fuelled development	+ RCP8.5 (high-end)
SSP4 Game of Elites	+ RCP4.5 (low-end)
SSP1 Sustainability	+ RCP4.5 (low-end)

SSP: Shared Socioeconomic Pathway
RCP: Representative Concentration Pathway

Table 6: Global model simulations conducted using the IMPRESSIONS RCP/SSP scenarios to evaluate impacts over Central Asia.

Global model	Sector(s)	Resolution	RCP (climate)	SSP (socio-economic)	Partner
Heatwave mortality	Human health	0.5° lon/lat	Temperature	Population	NIES. Japan
GLOBIO3	Biodiversity	0.5° lon/lat	Temperature, precipitation	Population; grazing intensity	Wageningen Univ./ PBL, Netherlands
WaterGAP2	Hydrology, water use	0.5° lon/lat	Temperature, precipitation	Population; GDP; technology; irrigation efficiency; water use	University of Kassel, Germany

4.2. Scenario-based global model results for central Asia

Some illustrations of the impact model results prepared for the second stakeholder workshop of the EUx study (Baku, May 2016) are presented in the following sub-sections. They are all derived from the WaterGAP2 model (see Appendix A1.5) and are organised according to the four scenario worlds in which discussions at the workshop took place (*cf.* Table 5). More details will be included in Deliverable D3A.2, which will report results from the EUx case study. Example results of water use modelling in the domestic and agriculture sectors for the scenarios SSP1, SSP3, SSP4 and SSP5 are shown in the following sections.

4.2.1. Sustainability (SSP1 x RCP4.5)

Regional domestic water withdrawals resulting from estimates of population and domestic per capita water use, which were quantified by stakeholders during the first stakeholder workshop for the different socio-economic scenarios, are shown in Figure 11 (right hand side). Changing attitudes towards resource use lead to a decrease in domestic water use per capita. Despite population growth, behavioural changes and technological improvements result in decreasing domestic water use in the long-term.

Three factors influence irrigation water demand in WaterGAP: climate, irrigation efficiency and irrigation area. WaterGAP results indicate that climate induced increases of irrigation water demand can be overcompensated by the assumed almost doubling of irrigation efficiency (Figure 11, left hand side). Due to agriculture being classified as being of medium importance as an economic sector in this scenario, irrigation area is kept constant.

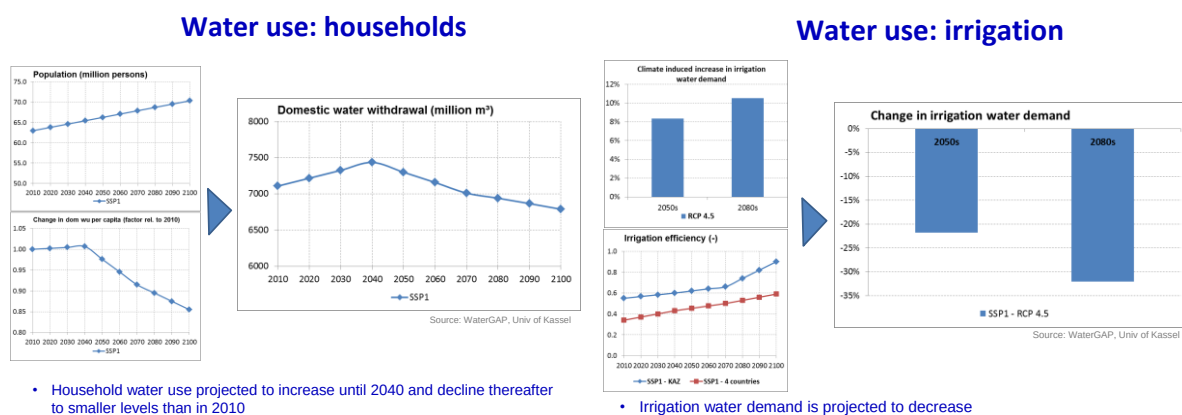


Figure 11: Change in water use for households and irrigation in Central Asia between the present-day and 2100 under the SSP1/RCP4.5 scenario based on the WaterGAP2 model.

4.2.2. Regional Rivalry (SSP3 x RCP8.5)

Out-migration in the 2040s eases pressure on water resources slightly. Political instability in the region accompanied by decreasing investments in water infrastructure lead to a strong increase in water withdrawals for domestic water supply. After 2070 political chaos and deterioration of infrastructure lead to decreasing water supply for the population reflected by decreasing per capita water use (Figure 12, left hand side).

The high economic and social importance of agriculture in this scenario leads to investments and considerable efficiency improvements in irrigation by 2030. Despite a temporary increase in irrigation

area by 5% (2030s) due to the high economic importance of agriculture, efficiency improvements are sufficient and maintained to compensate for climate change impacts on irrigation water demand (Figure 12, right hand side).

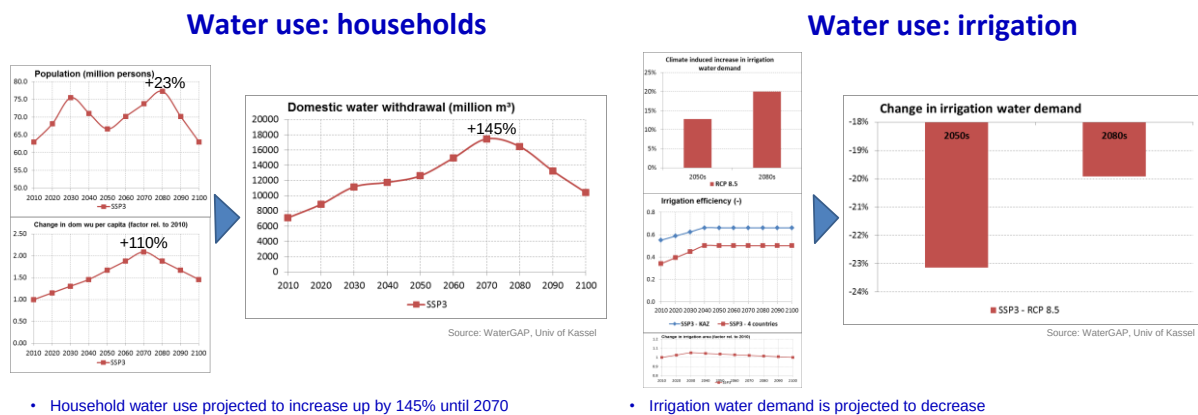


Figure 12: Change in water use for households and irrigation in Central Asia between the present-day and 2100 under the SSP3/RCP8.5 scenario based on the WaterGAP2 model.

4.2.3. Game of elites (SSP4 x RCP4.5)

In the domestic sector, a decrease of per capita water use compensates for an increase in population resulting in an almost stable water withdrawal (Figure 13, left hand side). In contrast to other scenarios, irrigation water demand increases due to climate change, low irrigation efficiency due to a lack of financial resources for the masses to invest in high tech equipment, and increasing irrigation area due to the high importance of agriculture as an economic sector and the necessity of maintaining the production level (Figure 13, right hand side).

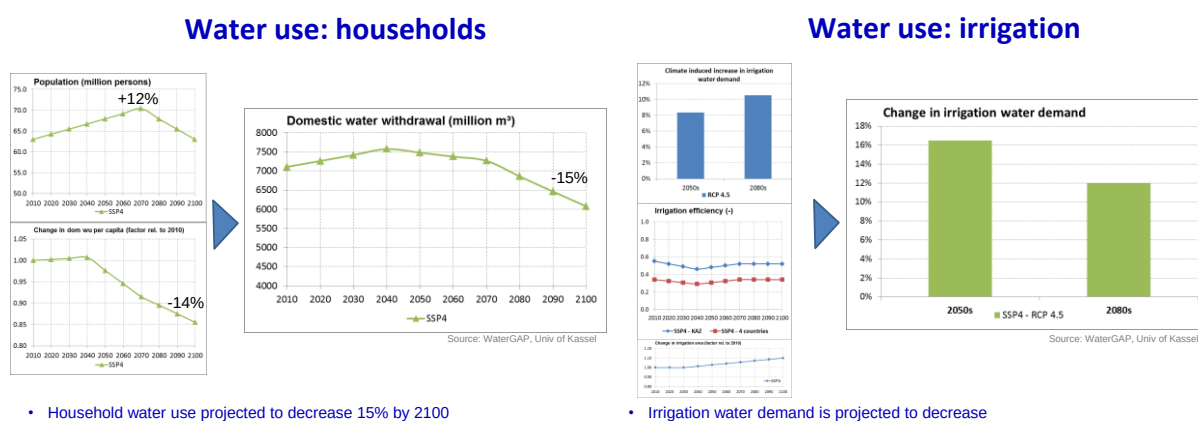


Figure 13: Change in water use for households and irrigation in Central Asia between the present-day and 2100 under the SSP4/RCP4.5 scenario based on the WaterGAP2 model.

4.2.4. Fossil-fuelled development (SSP5 x RCP8.5)

In this scenario, domestic water use increases by about 21% until 2100. This reflects increases in population coupled with a near stable domestic water use intensity (Figure 14, left hand side). In SSP5, irrigation area is assumed constant over time corresponding to the medium importance of agriculture

while food imports for the increasing population are affordable. A slight increase in irrigation efficiency, with a maximum in 2050 (+10% in Kazakhstan and +26% in remaining countries), is sufficient to compensate for climate impacts on irrigation water demand (Figure 14, right hand side).

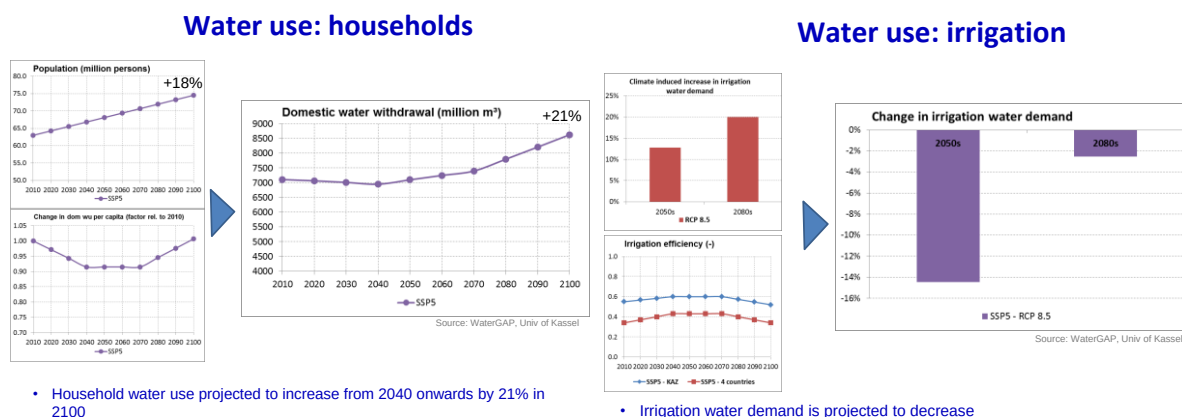


Figure 14: Change in water use for households and irrigation in central Asia between the present-day and 2100 under the SSP4/RCP4.5 scenario based on the WaterGAP2 model

5. Using global models to estimate the consequences of European adaptation strategies for the rest of the world

As adaptation to climate change takes place in Europe, these adaptation measures can be expected to lead to secondary effects in other parts of the world. For example, to guarantee imports of certain commodities whose supplies in some regions are at risk from climate change, European importers may switch to suppliers in different regions. Various adaptation pathways are being developed in the project, and where various measures can be simulated, their implications will be explored (alongside mitigation measures, as applicable) using global models. Some possible applications are shown in Table 7 for pathways already identified in WP4, with sample elements of those pathways shown for illustration. The specific application of global models will be contingent on their ability to simulate adaptation (or mitigation) measures consistent with a given adaptation pathway element. For this reason, the models listed are indicative only.

Table 7: Possible applications of global models to explore adaptation pathways in IMPRESSIONS.

Starting scenario	Adaptation pathway (from WP4)	Potential pathway elements	Global model to be used?
SSP1/ RCP4.5	1.4 Mainstream sustainable agriculture with eco-modernisation across Europe	Strengthen and scale CAP over time in Europe Support market introduction and diffusion of sustainable agriculture technologies and products Invest in sustainable agricultural technology and technology transfers	IMAGE M-GAEZ WaterGAP
SSP1/ RCP4.5	1.5 Strengthen and advance nature protection and restoration	Promote nature protection with stronger environmental policy Promote nature protection and restoration with mainstreaming nature-based solutions Advance integrated land use planning using an ecosystem services framework Adopt a holistic approach to water management	GLOBIO IMAGE WaterGAP VISIT
SSP3/ RCP8.5	3.3 Implement nature-based solutions and approaches for environmental protection and resilience	Strengthen policies and build skills for local organic agriculture Regenerate ecosystem services in cities and rural areas to build resilience	GLOBIO M-GAEZ
SSP3 / RCP8.5	3.4 Manage water to ensure high levels of quality, save water and protect from floods	Strengthen physical and social resilience to protect from flooding Implement water saving measures to ensure universal access to high quality water	WaterGAP
SSP4/ RCP4.5	4.3 Implement nature-based solutions to protect biodiversity and water resources	Strengthen biodiversity protection Implement land use and planning in harmony with nature Improve water efficiency and decrease water use	GLOBIO IMAGE WaterGAP
SSP4/ RCP4.5	4.4 Establish a circular economy with green energy technologies	Promote a circular economy with zero waste Strengthen Europe's market position in developing and applying green energy technologies	IMAGE
SSP5/ RCP8.5	5.3 Achieve food security and environmental protection through organic, family-based agriculture	Design an integrated and organic agricultural system Increase food security Incorporate ecosystems' services in agriculture life cycle Scale the CAP policy Introduce market-based instruments to support rural agricultural activities	M-GAEZ IMAGE
SSP5/ RCP8.5	5.4 Design markets to protect and regenerate ecosystem services and build resilience	Move from habitats to ecosystem services and create nature-based markets Work with nature to build resilience Invest in technology-based solutions for improving environmental quality and creating new markets	IMAGE GLOBIO VISIT
SSP5 / RCP8.5	5.5 Establish integrated, EU-wide water management or high water quality and reduced water use	Implement integrated management of water resources across Europe	WaterGAP

6. Comparing global model estimates of impacts with those from finer-scale models

Some global models deployed in the IMPRESSIONS project provide impact estimates for variables that are also simulated using finer-scale models. This provides an opportunity to compare model results for the same scenarios as one approach for determining structural uncertainties attributable to the choice of impact model. Table 8 lists those global models that have been identified as possible candidates for inter-comparison with finer-scale models in the project.

Table 8: Models applied in IMPRESSIONS that offer an opportunity for inter-comparison.

Issue/Sector	Models (coarse scale)	Models (finer scale)
<i>Global to European</i>		
Land use	IMAGE, iPETs, AIM	IAP2/rIAM, CRAFTY
Crop yields	IMAGE, iPETs, AIM	IAP2/rIAM, SWIM
Water availability/use	WaterGAP	IAP2/rIAM, SWIM
Species abundance	GLOBIO	IAP2/rIAM
Urban development	iPETs	RUG, IAP2/rIAM
Heat-rel. mortality	AIM/Impact[Health]	rIAM
Flooding	AIM	rIAM
<i>Global to regional</i>		
Water availability/use	WaterGAP	SWIM, IAP2/rIAM
Heat-rel. mortality	AIM/Impact[Health]	Hungary-mort. model
Urban development	iPETs	Hungary urban model

As illustration of such a comparison, some of the land use models applied in IMPRESSIONS and operating at different spatial scales have been recently compared (Alexander et al., 2016). The authors conducted an uncertainty assessment of global and European land cover projections over a diverse range of model types and scenarios and incorporating results from 75 simulations from 18 models. Alexander et al. quantified uncertainty for different land uses and the relative contribution from different sources of uncertainty obtained from an ANOVA analysis of simulation results (Figure 15). Systematic differences in land cover areas associated with the characteristics of the modelling approach were identified (green shading in Figure 15) to be at least as great as the differences attributed to the scenario variations. Their main conclusion is that “a higher degree of uncertainty exists in land use projections than currently included in climate or earth system projections” (Alexander et al., 2016). To account for land use uncertainty, it is recommended to use a diverse set of models and approaches when assessing the potential impacts of land cover change on future climate.

This work could be extended in IMPRESSIONS by undertaking a more in-depth inter-model comparison assessment for a consistent set of input scenarios related to the RCPs and SSPs. A protocol for the inter-model comparison work and other methods for quantifying uncertainties in impact model outcomes is currently under development and will be reviewed and finalised at the fourth IMPRESSIONS modellers meeting in November 2016.



Figure 15: Total coefficient of variation (i) and relative importance of different variance components (ii) contributing to modelled land use in Europe (EU27). In (ii) variance due to model characteristics is shown in different shades of green and due to scenario characteristics in different shades of red. Source: Alexander et al. (2016).

7. Acknowledgements

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Appendix 1: Description of global impact models applied in IMPRESSIONS

A1.1 Heat stress mortality from AIM/Health simulations

AIM/Health estimates excess mortality due to heat stress for each grid cell based on daily maximum temperature and population density. Daily excess mortality due to heat stress (DDNE) is defined as the difference between the daily mortality (DDN) and the daily mortality at the optimal temperature (DDNO) on days whose daily maximum temperature (T) is higher than the optimal temperature. The value of DDNE on a day whose T is lower than T_O is zero. The shaded areas in Figure A1 represent the annual excess mortality due to heat stress ADNE (number of deaths/year).

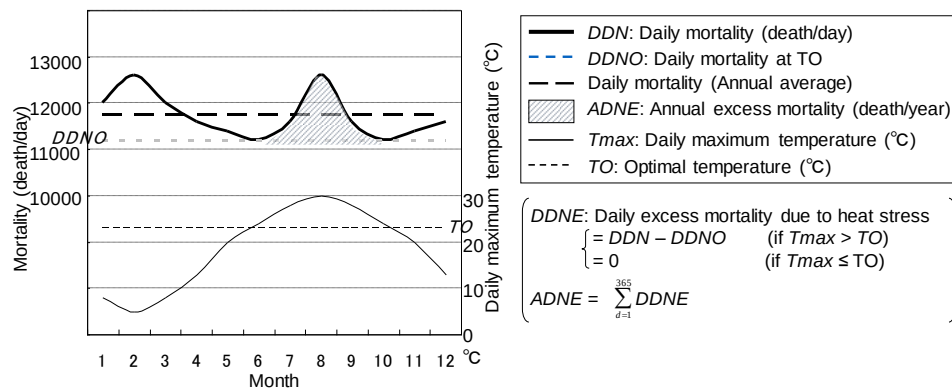


Figure A1: Definition of excess mortality due to heat stress in AIM/Health (Source: Takahashi et al., 2007).

A1.2 Crop yield from M-GAEZ simulations

M-GAEZ (Figure A2) is a crop productivity model, which is based on the Global Agro-Ecological Zones methodology (GAEZ – Fischer et al., 2002) and was modified as noted in Masutomi et al. (2009). It has the capability of estimating potential crops yield for 14 crops including rice, wheat and maize considering climate factors such as temperature, precipitation, radiation as well as some other environmental factors such as land characteristics and irrigation rate.

In the most recent version of the model, yield for each grid box is determined not only by biophysical conditions including climate ($1^\circ \times 1^\circ$) but also by management conditions including water management (rain-fed or irrigated) and input level, which is a collective indicator incorporating factors that affect yield (e.g. fertilization level, technological development level). The effect of CO_2 fertilization is accounted for by applying yield multipliers according to the mean atmospheric CO_2 concentration projected for a given time period. The spatial resolution of final output yield is $2.5' \times 2.5'$, which is then aggregated to give country-level yields (Tanaka et al., 2015).

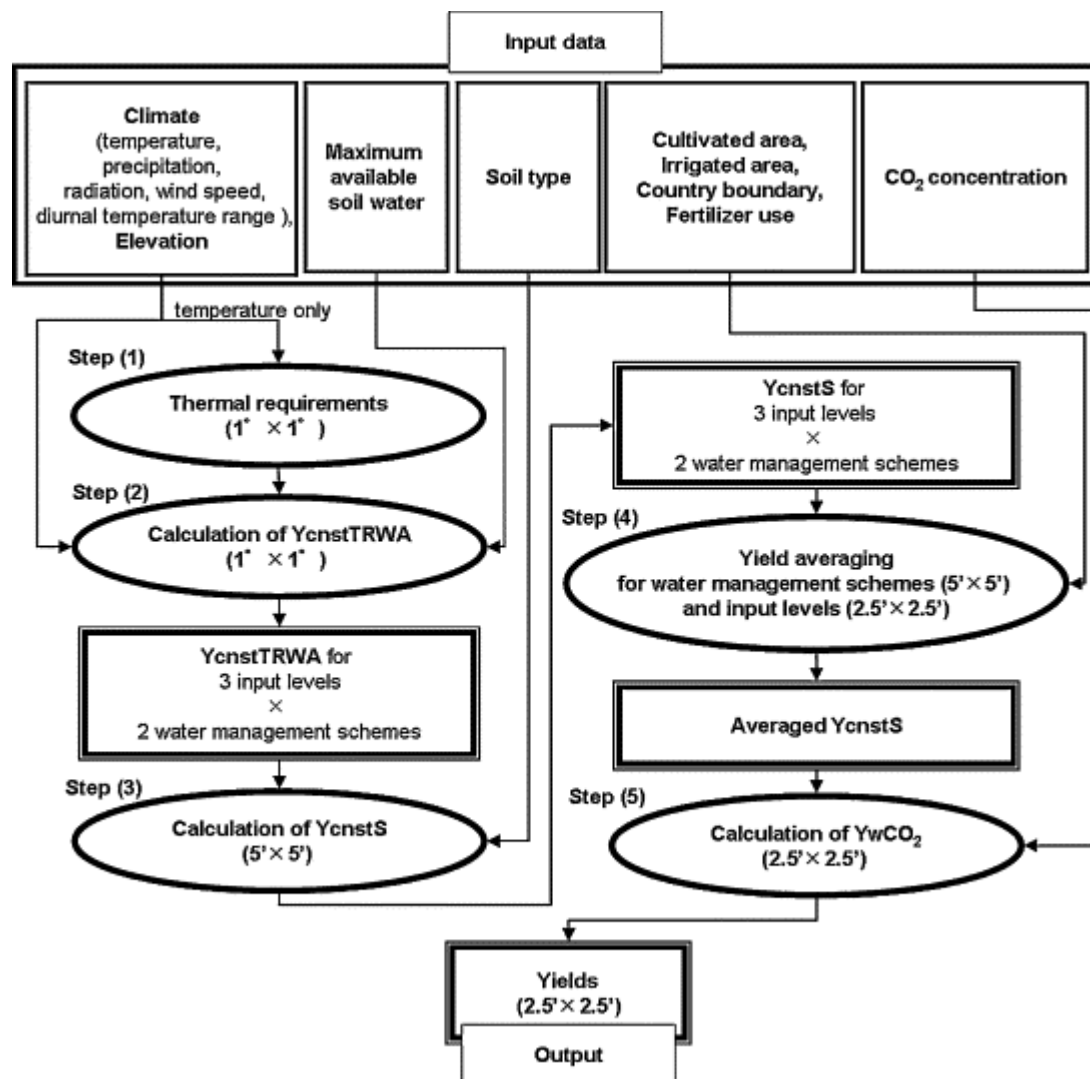


Figure A2: Procedures used to calculate yields in the M-GAEZ model (YcnstTRWA represents yields limited by temperature, radiation, water, and agro-climatic constraints; YcnstS represents yields with soil type constraint; and YwCO₂ represents yields with the CO₂ fertilization effect). Source: Masutomi et al. (2009).

A1.3 Net primary production from VISIT simulations

VISIT (Vegetation Integrative Simulator for Trace gases) is an integrated model for simulating the biogeochemical interactions, which would work as a component of Earth System Models in a supplementary manner with physical interaction schemes. The model consists of carbon, nitrogen, and water cycling schemes, which consider mutual interactions (Figure A3). Net primary production (NPP), one of the basic ecosystem functions, is obtained as a difference between plant's photosynthesis and respiration. The model aims to simulate the exchange of trace gases by terrestrial ecosystems for as many species as possible and as ecophysiologically as possible taking account of: photosynthetic and respiratory CO₂ budget, wetland and paddy field CH₄ emissions, upland CH₄ oxidation, nitrification and denitrification N₂O emissions (natural and agricultural), biomass burning emissions (11 species such as CO₂, CH₄, CO, BC, and OC), land use change CO₂ emissions (including time-lag), and BVOCs (nine species such as isoprene and monoterpene). Additionally, the model

includes carbon discharge by water erosion and leaching, which affects the mass-balance of ecosystems.

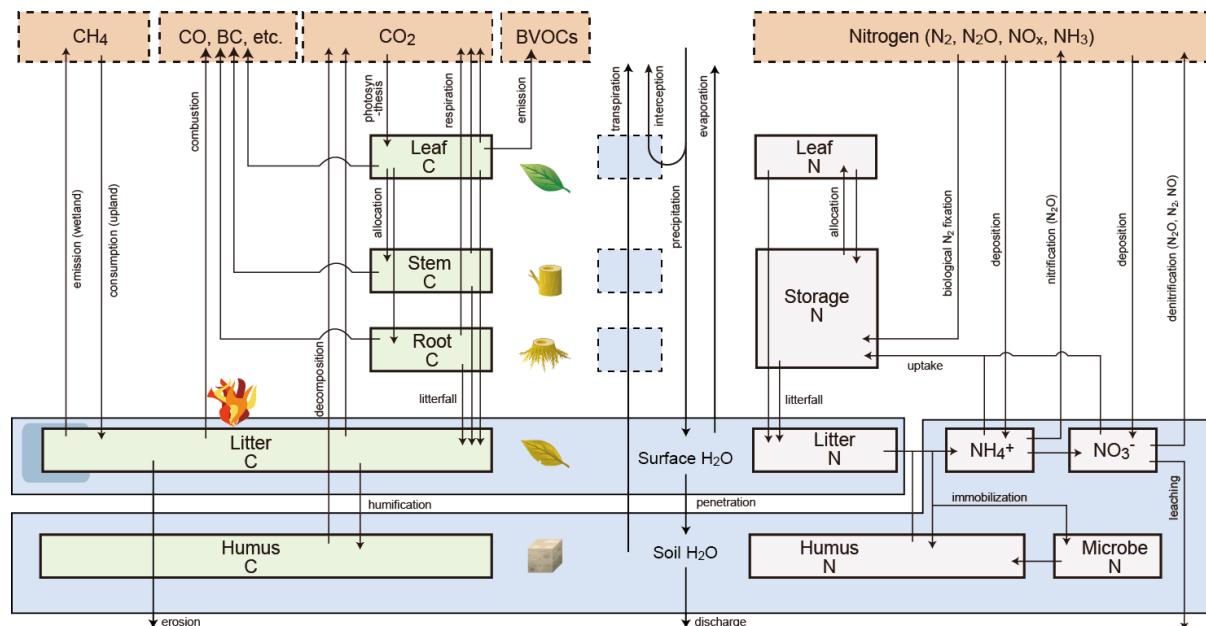


Figure A3: Model framework of the VISIT model. Source: based on Inatomi et al. (2010).

A1.4 Terrestrial biodiversity loss from GLOBIO simulations

The global biodiversity model GLOBIO assesses past, present and future human-induced changes on terrestrial biodiversity, expressed as the mean species abundance (MSA) (Alkemade et al., 2009). MSA indicates the mean abundance of original species in relation to a particular pressure as compared to the mean abundance in an undisturbed reference situation. GLOBIO applies cause-effect relationships to quantify the individual and combined effect of five direct anthropogenic environmental pressures: climate change, land use change, atmospheric nitrogen deposition, disturbance by infrastructure and fragmentation due to land use (Figure A4).

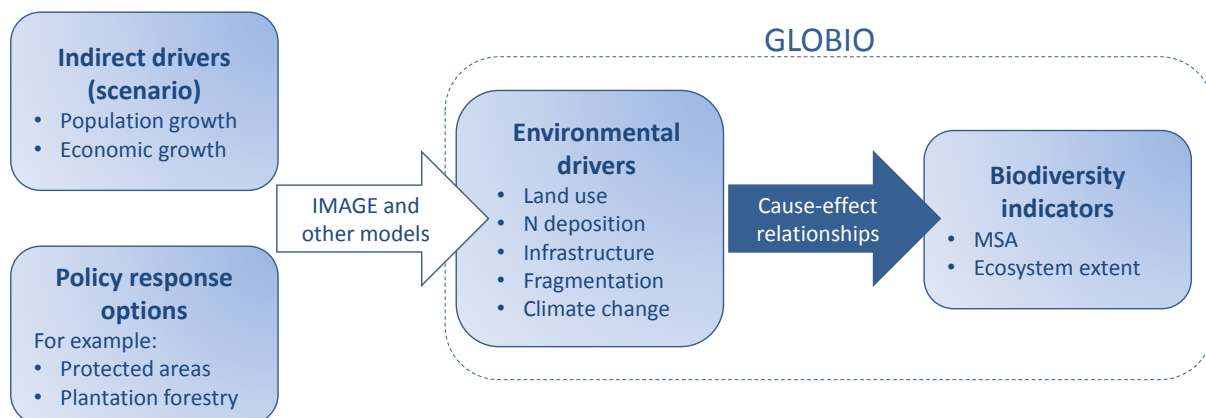


Figure A4: Representation of the GLOBIO model. Source: <http://www.globio.info/what-is-globio/how-it-works>.

A1.5 River discharge, water availability and water use from WaterGAP simulations

The WaterGAP2 model was developed at the Center for Environmental Systems Research at the University of Kassel in Germany and is a tool for computing indicators of water use and water availability on a global grid with $0.5^\circ \times 0.5^\circ$ spatial resolution or on a river basin level (Alcamo et al., 2003; Döll & Siebert, 2002). It comprises a hydrological model for simulating water availability, and a water use model, with several sub-models.

The aim of the hydrological model component is to simulate the characteristic macro-scale behaviour of the terrestrial water cycle in order to estimate water availability (Figure A5). Based on the time series of climatic data, the model calculates the daily water balance for each grid cell, taking into account physiographic characteristics such as soil type, vegetation, slope, and aquifer type. Runoff generated on the grid cells is routed to the catchment outlet according to a global drainage direction map (Lehner et al., 2008) taking into account the extent and hydrological effects of lakes, reservoirs, dams and wetlands. The model is calibrated by adjusting one free parameter, which controls the fraction of total runoff from effective precipitation in order to minimise the error in simulated long-term annual discharge.

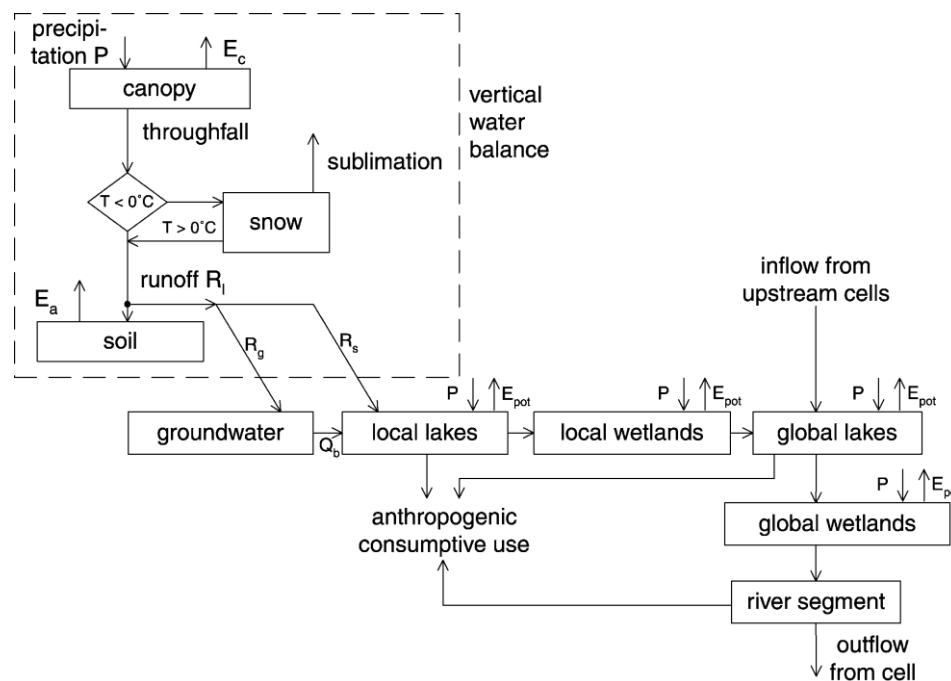


Figure A5: Schematic of the hydrology model of WaterGAP2 (P: precipitation, E_{pot} : potential evapotranspiration, E_a : actual evapotranspiration from soil, E_c : evaporation from canopy, R_l : lateral runoff, R_s : surface runoff, R_g : groundwater recharge). Source: Döll et al. (2003).

The Global Water Use model, consists of sub-models for the domestic, industry (not shown) and agriculture sectors in more than 160 countries. The Domestic Water Use model calculates annual withdrawals and consumption of water by households and small businesses. First domestic water use intensity (m^3 per capita per year) is computed from a sigmoid curve that describes the increase and eventual saturation of water use intensity relative to increasing income. Next, water use intensity is multiplied by national population. The model also takes into account the observed long-term trend in improving water use efficiency due to technological changes in the water supply infrastructure (Alcamo et al., 2003). The Agriculture Water Use model consists of two main components: a livestock

model and an irrigation model. Withdrawals for livestock are assumed to be equal to their consumption and are computed by multiplying livestock water consumption per head by the number of livestock. Irrigation water requirements are computed with a global irrigation model. Water consumption of irrigated crops is computed from their evapotranspiration rate and withdrawals are computed by assigning irrigation water use efficiency. The model takes into account climate variables, a global map of irrigated areas, types of cropping and the improvement in water use efficiency over time because of technological changes in irrigation methods. In most countries livestock water use is much smaller than irrigation water use.

For the most recent version, WaterGAP3, the spatial resolution of the model raster has been increased from 30' x 30' to 5' x 5'. In addition, the model was enabled to operate on daily time steps. Partly enabled by this finer resolution, the process representations of runoff formation and runoff concentration in the hydrological model have been substantially improved, including (i) snow dynamics on the sub-grid scale (Verzano & Menzel, 2009), (ii) implementation of a variable flow velocity algorithm (Schulze et al., 2005), (iii) introduction of a meandering factor to improve the representation of river length (Lehner et al., 2008), and (iv) estimation of potential evapotranspiration and ground water recharge taking into account Köppen's climatic regions (Weiß, 2009). These model revisions are a prerequisite for the application of WaterGAP3 to analyse the hydrological extremes in addition to long-term water availability. The model's general ability to simulate flood discharges has been evaluated by Verzano (2009).

A1.6 iPETS

The integrated Population-Economy-Technology-Science model, known as iPETS, is an integrated assessment model under development that combines human and earth systems to help understand how key aspects of society may evolve in the future and how they might interact with a changing climate.¹ iPETS links three component models: a demographic model, an energy-economic model, and a simple climate and atmospheric composition model (Figure A6). The Community Demographic Model (CDM) has four components designed to project population by age, gender, urban versus rural residence, and household type for at least 31 world regions at a grid-cell level. The Population-Environment-Technology (PET) model is a global energy-economic model that provides the economic core of the iPETS model. It is a multi-region, multi-sector computable general equilibrium (CGE) model with forward looking behaviour, and projects economic growth, energy use, land use, and carbon emissions. The Integrated Science Assessment Model (ISAM) is a globally aggregated model of the carbon cycle, other greenhouse gases and aerosols, and the climate system that links with the PET model. There are several versions of ISAM with varying complexity. Currently iPETS links PET with the simpler version of ISAM, but work is underway to link to a more complex version.

¹ <https://www2.cgd.ucar.edu/sections/tss/iam/iam-modeling>

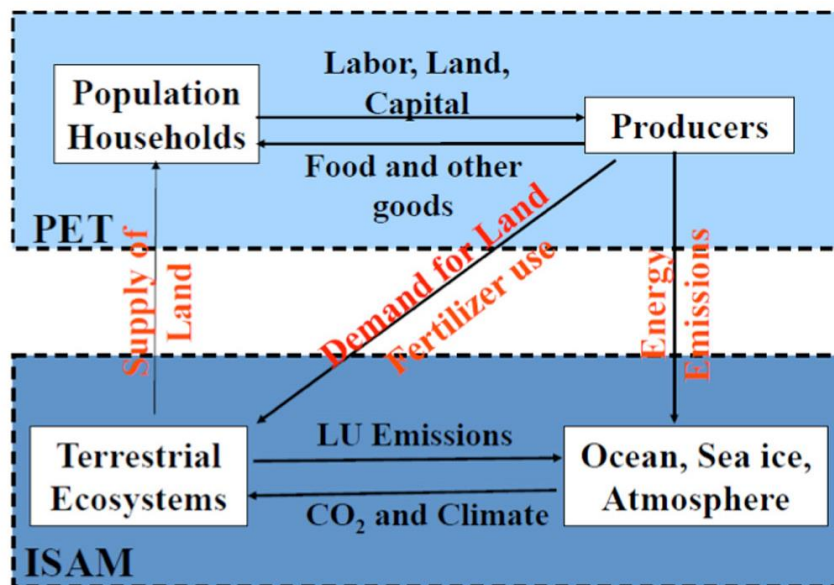


Figure A6: Components of the iPETS global regionally disaggregated integrated assessment model. Source: NCAR RAL Annual Report (2009).

A1.7 IMAGE 3.0

IMAGE 3.0 (Integrated Model to Assess the Global Environment, version 3.0) has been developed by the IMAGE team under the authority of PBL Netherlands Environmental Assessment Agency, building on earlier efforts dating back over three decades (IMAGE 1.0 was published in 1990; IMAGE 2.0 in 1994). The IMAGE 3.0 website contains information and documentation of the model, at: http://themasites.pbl.nl/models/image/index.php/Welcome_to_IMAGE_3.0_Documentation.

IMAGE is described as "an ecological-environmental model framework that simulates the environmental consequences of human activities worldwide. It represents interactions between society, the biosphere and the climate system to assess sustainability issues such as climate change, biodiversity and human well-being (Figure A7). The objective of the IMAGE model is to explore the long-term dynamics and impacts of global changes that result from interacting socio-economic and environmental factors."

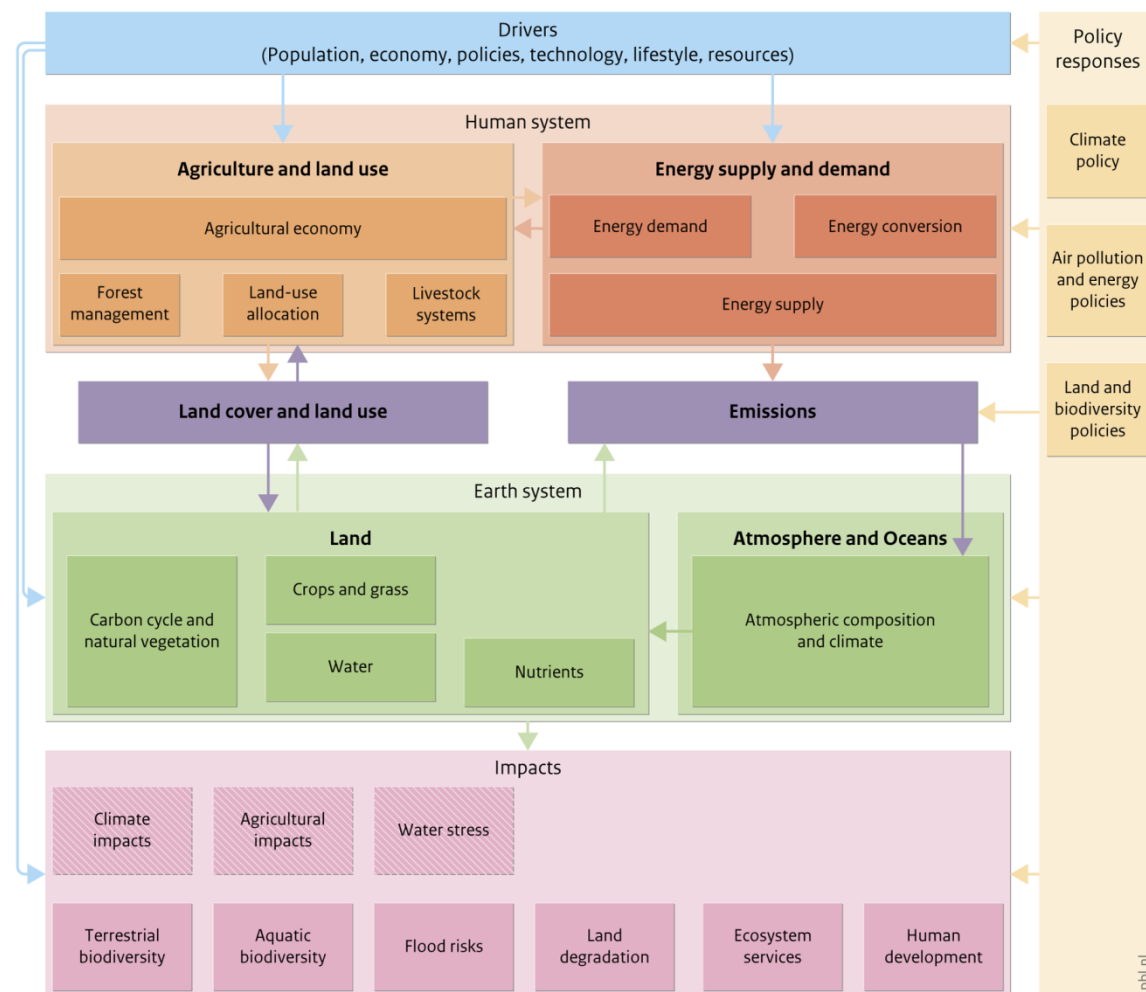


Figure A7: The IMAGE 3.0 Framework. Source: Stehfest et al. (2014).