Set of integrated high-end, multi-scale scenarios

Deliverable D2.4

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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 original intention of this final Deliverable of WP2 was to provide an overview and synthesis of the multi-scale climate and socio-economic scenarios produced within WP2. Over the course of IMPRESSIONS, however, it became clear that integration of climate and socio-economic scenarios can only be meaningfully attempted when accounting for differences in the nature of data (qualitative stories and quantitative models) and to some assessment of climate change impacts. In IMPRESSIONS, this is the objective of WP3 related to development and application of a range of climate change impact, adaptation and vulnerability models. As a result, the final deliverable of WP2 has a stronger focus on the analysis of the climate and socio-economic scenarios across the multiple scales of the IMPRESSIONS case studies and discusses modelling as a crucial tool to integrate climate and socio-economic scenarios, although with other forms of scenario integration are also presented.

Summary

The final objective of WP2 is to develop multi-scale, integrated climate and socio-economic scenarios for five case studies. This deliverable builds on socio-economic and climate scenarios as documented in Deliverable D2.2 (Kok and Pedde, 2016) and Deliverable D2.3 (Madsen et al., 2016), respectively. The main objective of this deliverable is to report on the final set of integrated climate and socio-economic scenarios across scales, including tipping points.

The analysis of the climate scenarios concludes that model uncertainty is high and that model selection is not a straightforward task as there is no single set of performance metrics. When using multi-model ensembles, care should be taken to avoid uncertainty being overestimated as climate change in one region is not independent of change in other regions. The sub-sampling of GCMs for impact shows that model spread is larger for the smaller regions and larger in summer. A number of large-scale tipping points are identified, even though there is a very low level of agreement between climate models on their occurrence.

The analysis of the socio-economic scenarios shows that there are strong differences, as well as similarities, across scenarios expressed in different worldviews in the narratives and/or different quantifications of key model parameters and/or different actor capacities. Within the set of scenarios, SSP1 has the most positive future outlook based on an egalitarian worldview, with high levels of capital and actor capacities, which is reflected in a rather low population pressure. SSP3, in contrast, has the most negative future outlook based on a fatalist worldview, with low levels of capital and actor capacities and a high population pressure. SSP4 and SSP5 take intermediate positions. In general, differences across scales are smaller than across scenarios.

The climate and socio-economic scenarios were integrated and presented as a set of synthesising stories. The most important manner to integrate scenarios in IMPRESSIONS was through the use of a cross-sector model (the IMPRESSIONS Integrated Assessment Platform 2, IAP2). Results show that the IAP2 captures the complexity of the system beyond a simple addition of separate input parameters. Scenarios were also integrated by stakeholders adjusting SSPs based on climate change impacts. Introducing these impacts led to changes in the SSPs. Most changes related to a more rapid institutional and organisational change, while maintaining the overall logic of the scenario narratives. Four synthesising stories of combinations of RCPs and SSPs show four extremely diverse futures.

Overall, it is concluded that a wealth of innovative methods and resulting (integrating) scenarios have been produced that deserve to be further tested and used beyond the duration of IMPRESSIONS. The set of selected SSP×RCP combinations proved sufficient to create a diverse set of high-end integrated scenarios. The main recommendation is to use mixed methods when integrating socio-economic and climate scenarios, but to use (improved) models as the main tool for integration.

1. Introduction

The final objective of WP2 is to develop multi-scale, integrated climate and socio-economic scenarios for five case studies: Europe, Scotland, Iberia, Hungary and Central Asia (as part of an EU external (EUx) case study). This deliverable builds on socio-economic and climate scenarios as documented in Deliverable D2.2 (Kok and Pedde, 2016) and Deliverable D2.3 (Madsen et al., 2016), respectively. Both deliverables describe the scenarios produced, with a short analysis and cross-case comparison. The two types of scenarios consist of different types of products, reflecting the different domains that they analyse. The climate scenarios analysis relates to uncertainties in physical systems by using model simulations at multiple scales. The robustness of these scenarios, therefore, is strongly linked to the choice of modelling projections with multiple spatio-temporal trade-offs. The socio-economic scenarios analysis relates to uncertainties in the social system and its interaction with the environmental system. These scenarios have a stakeholder-determined qualitative component and an expert-based modelling component (Pedde et al., 2018).

Because of their different nature, the methods to perform a multi-scale analysis of socio-economic and climate scenarios also differs, which relates to different epistemologies, approaches and perspectives. Methods to develop (multi-scale) climate scenarios aim at sub-sampling and downscaling GCMs and minimising spatio-temporal model spread across case studies and for changes in annual and seasonal temperature and precipitation. Multi-scale socio-economic scenarios relate to downscaling existing scenarios (Kok et al., in review), during participatory workshops. Compared to the methodological downscaling focus of climate scenarios, the socio-economic scenario methodology can be defined as "cross-scale", with global SSP scenarios defining the boundaries for developing multi-scale nested stories (as in Deliverable D2.2) or as starting point for interrogating the role of local information to understand European-scale scenarios. For both climate and socio-economic scenarios, we discuss tipping elements in the systems as critical thresholds beyond which transitions to a different state occurs.

Partly because of the separate methods, results and analyses, this deliverable starts with a number of sections that present a separate analysis rather than an integration. Sections 2, 3 and 4 are the core of the analysis. Each section introduces what type of uncertainty is analysed with the scenario products (sections 2.1, 3.1. and 4.1), and the different methodological angles for the cross-scale analysis (2.2 and 2.3, 3.2, 4.2). Scenario integration is undertaken in three ways. In sections 2 and 3, the climate and socio-economic scenarios are analysed separately. In section 4, climate and socio-economic scenarios are analysed together, and different methods of integration are introduced and results analysed. In section 5, products, methods and applications are synthesised. Section 6 provides key methodological recommendations.

2. Analysis of climate scenarios

Climate scenarios have been developed for all five case study regions in IMPRESSIONS. The global scenarios are based on a sub-set of global climate model simulations available from CMIP5 (Coupled Model Inter-comparison Project Phase 5, Taylor et al., 2011). For the European and local case study regions it was decided to make use of the higher resolution regional climate model simulations available from Euro-CORDEX with a resolution of 50 km. Table 1 provides a list of scenario data available for each region.

Table 1: IMPRESSIONS scenario data. List of scenario data available for each region.

Region	Scenario/Impact model	Horizontal resolution	Time resolution	Climate model data
Global	GCM data (bias adjusted for -60-60°E, 0-90°N)	0.5°	Daily data	GCM
Europe	Bias-adjusted RCM data	0.5° and 10'	Daily data	RCM
Europe	Needed by impact model: rIAM	10'	Decadal time slices	RCM
Europe	Needed by impact model: IAP2	10'	30-year time slices	RCM
Scotland	Needed by impact model: IAP2 – Scotland	5km	30-year time slices	RCM

A subset of climate models were selected from the CMIP5 ensemble to represent high as well as moderate climate change. The selected sub-set of climate models is shown in Table 2.

Table 2: The core set of climate models selected for use in IMPRESSIONS. The last column denotes the magnitude of projected global temperature change (2071-2100 vs. 1981-2010) for each of the selected GCMs; high-end is above 4°C, intermediate is 2-3°C, and low-end is between 1 and 1.5°C.

	GCM	RCM	Climate change
RCP8.5	HadGEM2-ES	RCA4	High
	CanESM2	CanRCM4	High
	IPSL-CM5A-MR	WRF	High
	GFDL-ESM2M	RCA4	Intermediate
RCP4.5	HadGEM2-ES	RCA4	Intermediate
	MPI-ESM-LR	CCLM4	Low
	GFDL-ESM2M	RCA4	Low

The selection criteria were described in detail in Deliverable D2.1 (Kok et al., 2015). In Deliverable D2.3 (Madsen et al., 2016) we presented the seasonal mean changes of temperature, precipitation, short-wave radiation, humidity (specific and relative) and wind speed for each of the selected GCMs (and RCMs) to illustrate model spread within the IMPRESSIONS core set of climate models. We also described the bias-adjustment methods in detail and provided a comparison of the GCM vs. RCM climate change signal before and after the bias-adjustment.

In this deliverable we address how multi-model ensembles can be used to interpret the uncertainty of climate change projections at local, regional and global scales. We also investigate how well the selected subset of global climate models represent the spread in temperature and precipitation projected by the full CMIP5 ensemble for each of the IMPRESSIONS case study regions (i.e. Europe, Scotland, Iberia, Hungary and Central Asia). The implications of climate tipping points are also discussed.

It is generally advised to use as many climate models as possible and to use at least the core subset of the seven RCP-GCM-RCM combinations. However, for practical reasons, only the HadGEM2-ES-RCA4 projections (RCP4.5 and RCP8.5) were included in the IMPRESSIONS stakeholder workshops and some of the IMPRESSIONS studies rely on only these projections. We explore how well these models represent the climate model uncertainty in the various case study regions.

2.1. Uncertainty in climate scenarios across spatial and temporal scale

Uncertainty in climate model projections arise from three main sources: (i) scenario uncertainty (i.e. the uncertainty in future emissions); (ii) model uncertainty; and (iii) internal variability of the climate system. Uncertainty in future emissions becomes increasingly important for long-term projections and dominates towards the end of the century. This uncertainty may be explored by performing simulations for a range of emission scenarios. As IMPRESSIONS focuses on high-end climate change, we use RCP4.5 and RCP8.5 to represent intermediate and high-end emission scenarios.

Model uncertainty represents the imperfect representation of climate processes in models and it is advised to use as many climate models as possible to account for the uncertainty due to model inconsistencies. For near-term and local scale projections, the uncertainty is dominated by the internal variability in the climate system. As model agreement is better at larger scales, results from global climate models are more robust when presented as means over larger regions. Models agree quite well on the patterns and magnitude of climate change when the external forcing is strong. For weaker forcings, internal variability plays a larger role and models agree less well. Inter-comparison of models also shows a systematically better agreement for temperature than precipitation.

Global Climate Models (GCMs) are coarse resolution models that are used to gain knowledge about large-scale interactions and feedbacks in the climate system. For GCMs, present-day biases in temperature and precipitation are smaller at larger scales (Masson and Knutti, 2011). Because of the higher spatial and temporal resolution, regional climate model (RCM) projections usually have smaller biases than GCM data (i.e. compare better with present-day observations).

The multi-model mean generally provides a more robust estimate than a climate change projection from a single climate model (e.g. Gleckler et al., 2008). However, multi-model averages show less spatial variability and less extreme local values than single model projections (Knutti et al., 2010) and, for impact assessments, the large-scale average is most often not a sufficient representation of the local climate conditions. Instead, internally consistent time series of a number of climate variables are often needed, and in this case climate scenarios are most often based on results of single climate models that are selected from the full ensemble.

Model selection is not a straightforward task as there is no single set of performance metrics that can be applied to discriminate between good and bad performing models (Reichler and Kim, 2008; Gleckler et al., 2008). Also, there is no indication that models that simulate present-day climate most realistically will also be the models that perform best with respect to future climate. In fact, feedback processes that could have a large impact in a future climate (e.g. by affecting tipping elements) could be described poorly in a model that performs very well for present-day conditions far away from the tipping point. Therefore, model selection is often done using *ad-hoc* procedures based on regional model spread to ensure that the selected sub-set represents a sufficiently large fraction of the model uncertainty.

2.2. Uncertainty in multi-model ensembles

The regional model spread in an ensemble of climate models is often (e.g. IPCC, 2013) illustrated by collecting all model information and evaluating the statistics grid point by grid point. As part of the cross-scale analysis in IMPRESSIONS, we have investigated how this way of using model ensemble information contributes to the uncertainty at various scales. The following analysis is based on the material published in Madsen et al. (2017).

Figure 1 shows the spread in projected changes in mean annual temperature and precipitation (2081-2100 vs 1986-2005) derived from 39 CMIP5 simulations using the RCP8.5 emission scenario. The figure compares the grid point approach (Figure 1a, upper panel) with an approach where statistics are evaluated at the model level (i.e. each panel shows the change projected by one single model). For temperature, the differences between the two approaches are evident for the minimum and maximum rankings but also visible for the 25th and 75th percentiles (Figure 1, lower panel). For precipitation, the total spread (min to max) is very large for grid point statistics, and the patterns derived at the grid point level are very different from those based on individual models (Figure 1b, upper and lower panels).

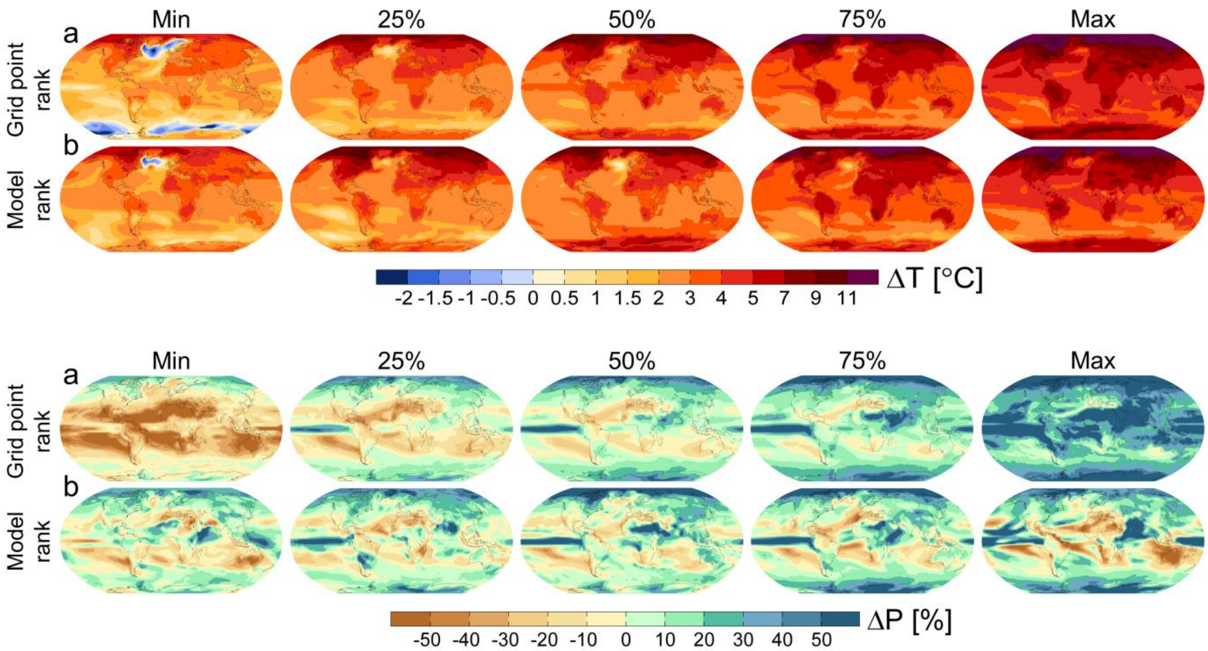


Figure 1: Grid point and model statistics for temperature (upper) and precipitation (lower) changes (2081-2100 vs 1986-2005) for the RCP8.5 scenario (Figure adapted from Madsen et al., 2017).

When aggregated to the global scale, we find that the range of the temperature change was significantly larger for grid point statistics (1.9 – 5.8K) than for model statistics (2.5 – 5.0K) and the difference between the two approaches is significantly larger for precipitation. This clearly shows that care needs to be taken if information for different grid points is extracted from different models as the total uncertainty may be inflated at larger scales (Madsen et al., 2017).

Grid point statistics are most often used to visualize the spread in climate change, but a similar way of regional ranking is often applied when a sub-set of climate models is selected for use in impact studies. Figure 2 compares the spread in climate change signal for temperature and precipitation for Europe applying global and regional ranking as well as grid point statistics. As before, the differences between the three ways of ranking are significantly larger for precipitation than for temperature. For Europe, the regional ranking is a balance between the increase in precipitation in northern Europe and the decrease in southern Europe and there are clear differences between the grid point approach and the regional ranking.

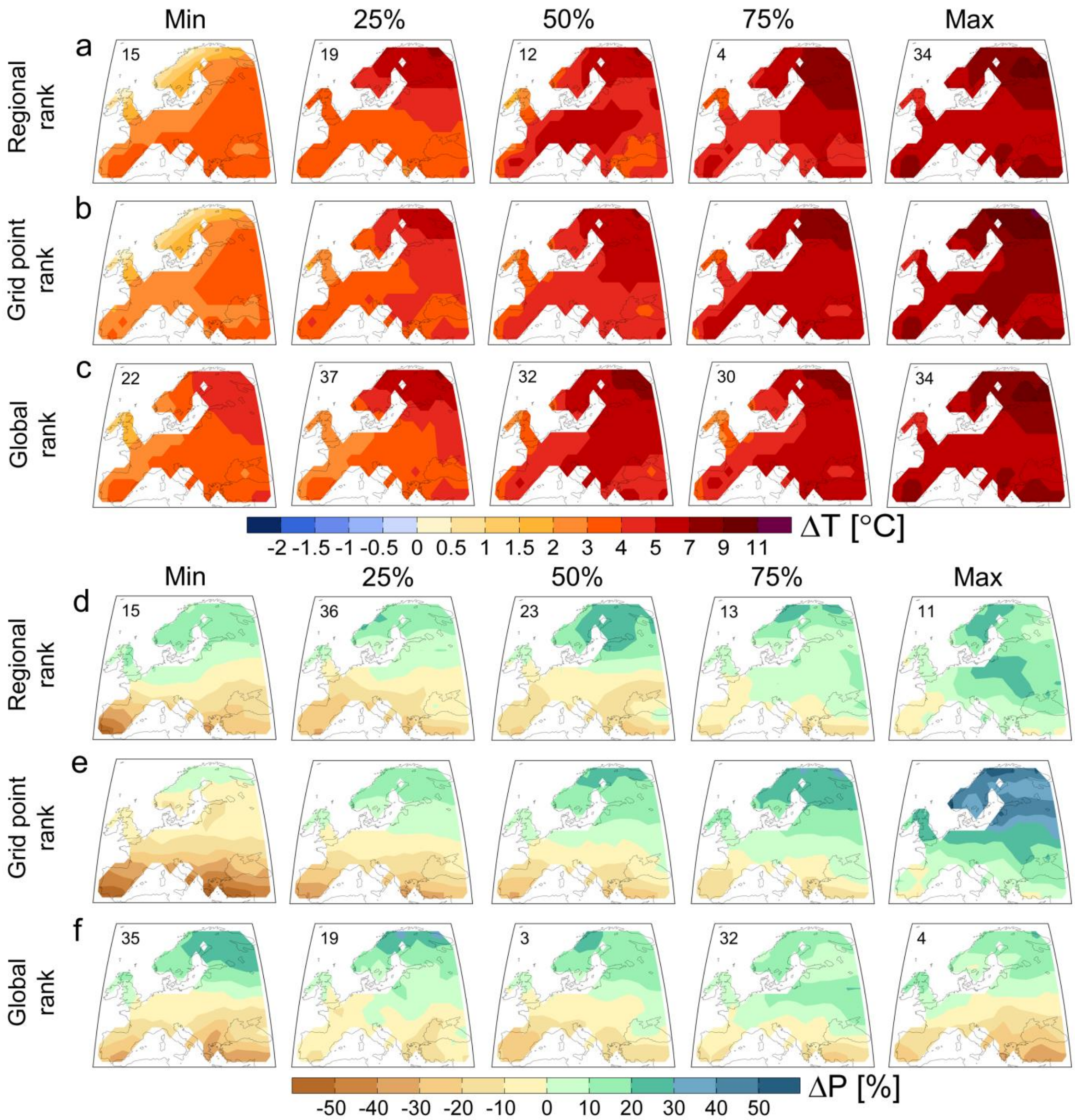


Figure 2: Grid point and model statistics for temperature (a-c) and precipitation (d-f) changes (2081-2100 vs. 1986-2005) for Europe (Figure adapted from Madsen et al., 2017).

Figures 3 and 4 compare the three methods for Iberia and Scotland, respectively. For Iberia, the regional ranking is very similar to the grid point ranking for temperature as well as precipitation. For precipitation, the regional ranking shows that at least one of the models projects a small increase in precipitation at least locally in parts of the region (Figure 3d and 3e). From the global ranking we find that the model with the highest increase in global precipitation projects less precipitation for Iberia. Very similar issues occur for Hungary (data not shown).

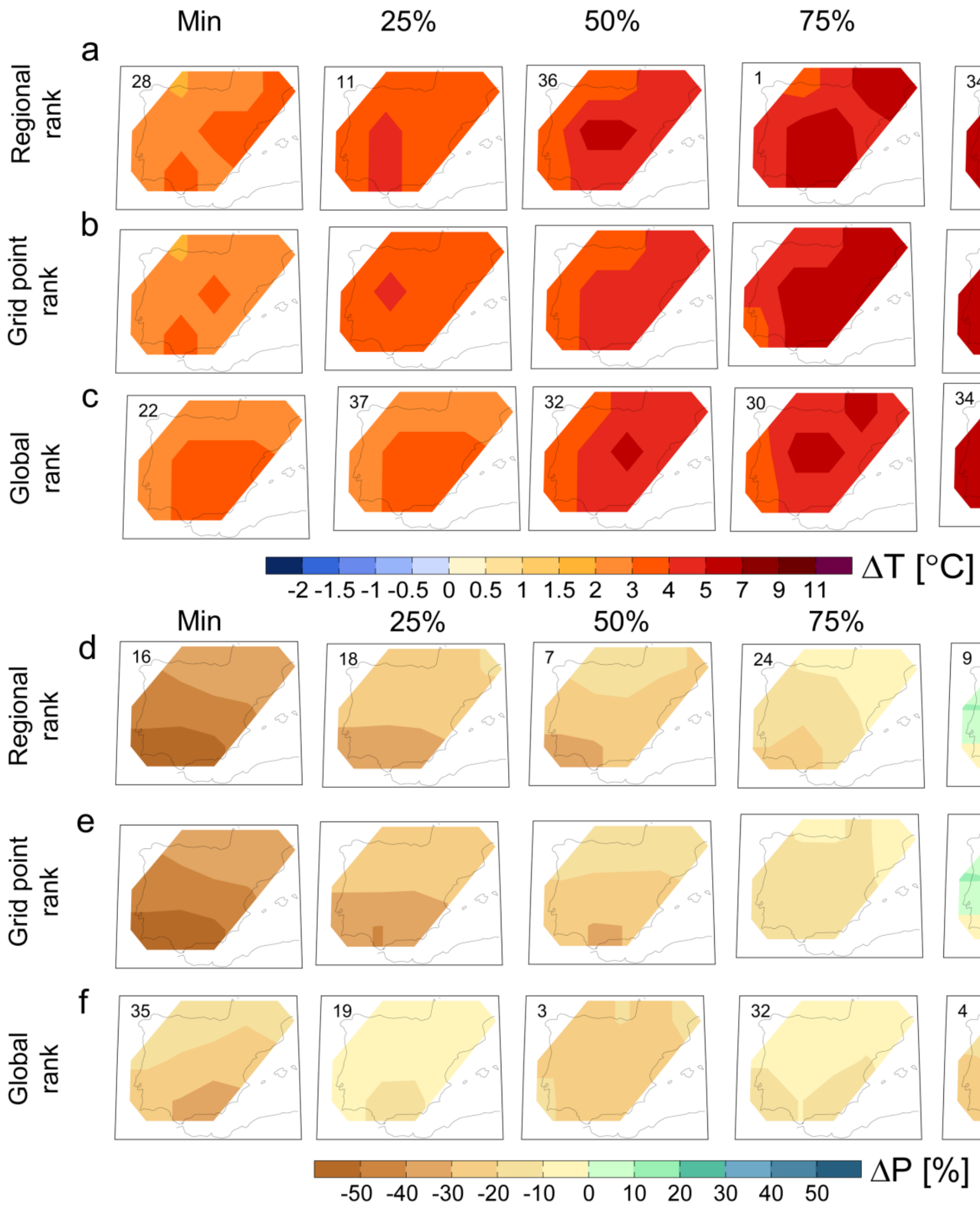


Figure 3: Model and grid point statistics for temperature (a-c) and precipitation (d-f) changes (2081-2100 vs. 1986-2005) for the Iberian Peninsula. Note that the form of the coastline is not well-represented in the low resolution GCM data.

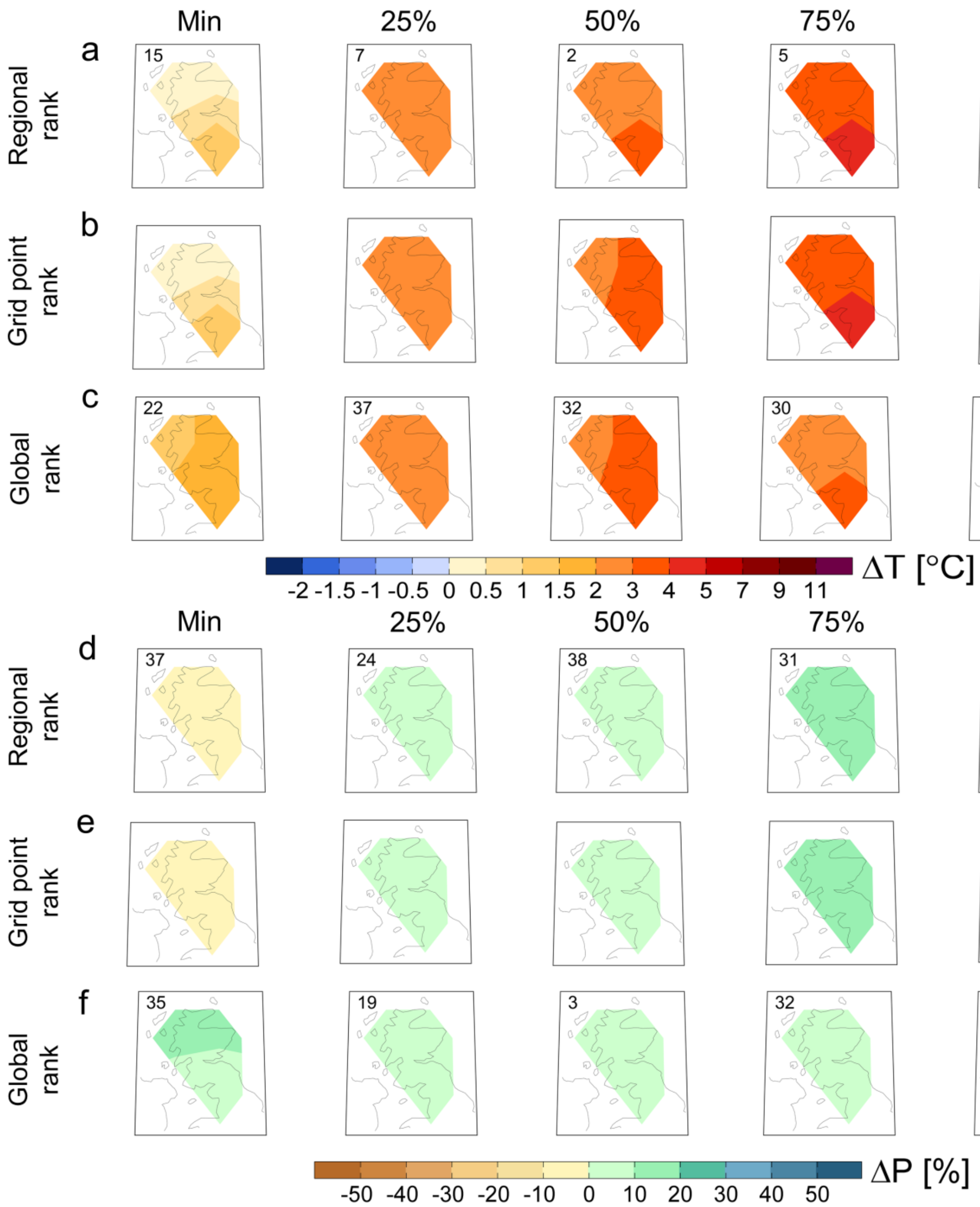


Figure 4: Grid point and model statistics for temperature (a-c) and precipitation (d-f) changes (2081-2100 vs. 1986-2005) for Scotland.

For Scotland, the regional ranking shows that there is a possibility for reduced precipitation. This is not captured in the global ranking approach as the model with the smallest increase in global precipitation is relatively wet over Scotland. Figures 3 and 4 illustrate that for small regions, regional ranking is quite similar to the grid point approach and exhibits the same issues when it comes to consistency at larger scales. This shows that model ranking at the very local scale is very similar to the grid point approach and thus may lead to similar inconsistencies. If the model with the most extreme local climate change is selected everywhere, this would result in a larger uncertainty than projected by any individual model when aggregated globally or even regionally.

Our analysis emphasises that care should be taken to avoid uncertainty being overestimated when multi-model ensembles of global climate models are used to extract regional climate information for impact assessments. Climate change in one region is not independent of climate change in a different region as largest (smallest) changes cannot occur everywhere at the same time without violating global constraints; if regional climate scenarios are developed region by region, this will not allow for a consistent cross-regional comparison.

Our findings further illustrate that there is no optimal way of selecting a subset of climate models from the full ensemble; if models are selected so as to represent the regional spread in climate change signals, this will not be consistent at the global scale. On the other hand, if models are based on global criteria, the projected spread in regional climate change projected by the full ensemble might not be well represented by the subset.

2.3. Sub-sampling GCMs for impact work in IMPRESSIONS

Even if it is not straightforward to select the most appropriate subset of climate models, a smaller and more workable set of climate scenarios was needed for IMPRESSIONS impact work. As the IMPRESSIONS scenarios should focus on high-end climate change, we have used global climate sensitivity as the main selection criterion. As described above, a global selection criterion ensures that the scenarios as well as the related impact assessments are comparable across local and regional case study regions. However, using this procedure, there is no guarantee that the sub-ensemble reflects the spread in projected regional climate change. In the following we investigate to what extent the model spread projected by the CMIP5 models is represented by the selected subset in each of the case study regions. The focus is on changes in annual and summer mean temperature and precipitation.

The scatter plots in Figures 5 and 6 illustrate how the temperature and precipitation changes (2071-2100 vs 1981-2010) projected by the selected subset of GCMs compare with those of the full set of 39 CMIP5 models at different scales and for summer and annual changes. The figures also indicate the HadGEM2-ES model that was used for the stakeholder workshops. For annual global scale changes, the distribution of the selected models (green for RCP4.5, yellow for RCP8.5) nicely reflects the selection criteria. We have three models that represent high-end climate change – the main focus – two models in the middle (one RCP4.5 and one RCP8.5) and two low-end models (RCP4.5). The selected high-end models are the only high-end ones downscaled in CORDEX, while more models with an intermediate climate change signal have been downscaled. The scatter plots clearly illustrate that model spread is larger for the smaller regions and also larger in summer than annually (Figures 5 and 6). In general, the selected subset represents the spread of the full model ensemble relatively well but there are important differences between the sub-regions.

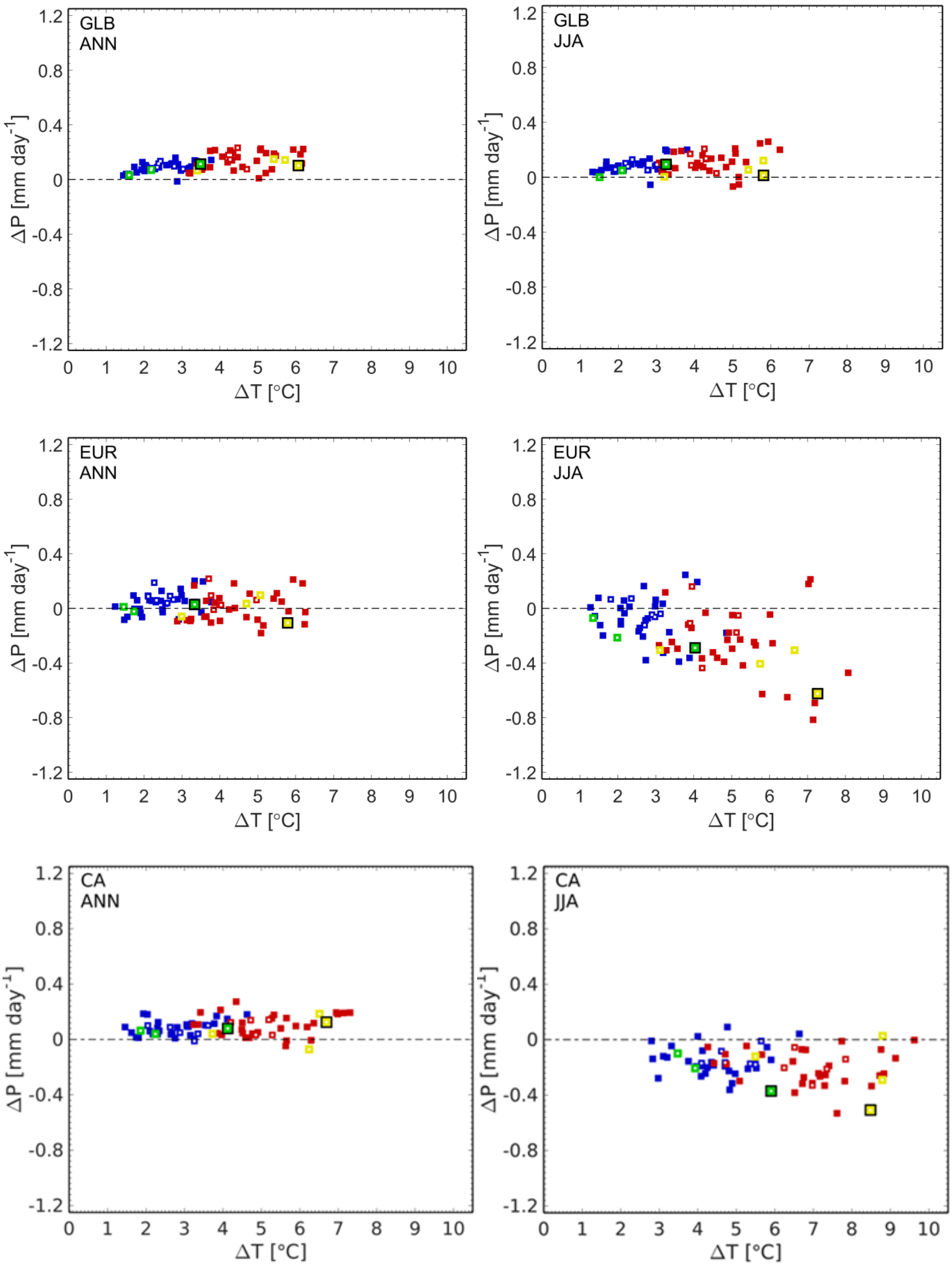


Figure 5: Global (top row), European (middle row) and Central Asian (bottom row) changes in temperature and precipitation (2071-2100 versus 1981-2010) for an ensemble of 39 CMIP5 models. The selected subset is marked as yellow (RCP8.5) or green (RCP4.5). For the remaining GCMs, blue squares denote RCP4.5 and red squares denote RCP8.5. A white square in the middle indicates that the GCM was dynamically downscaled with data available from CORDEX. The black boxes mark the HadGEM2-ES simulations which were used as input for the stakeholder workshops.

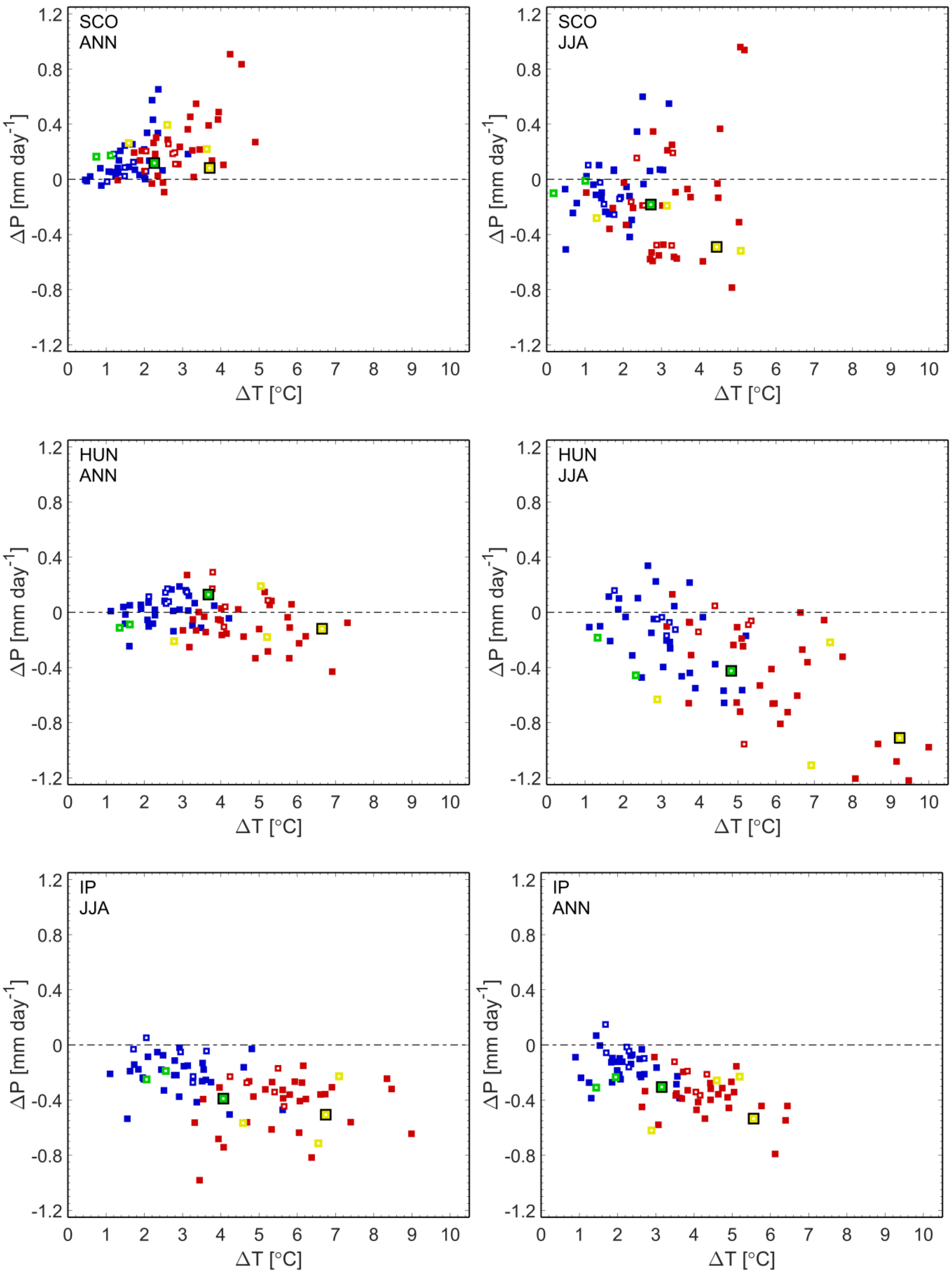


Figure 6: Scottish (top row), Hungarian (middle row) and Iberian (bottom row) changes in temperature and precipitation (2071-2100 versus 1981-2010) for an ensemble of 39 CMIP5 models. The selected subset is marked in yellow (RCP8.5) or green (RCP4.5). For the remaining GCMs, blue squares denote RCP4.5 and red squares denote RCP8.5. A white square in the middle indicates that the GCM was dynamically downscaled with data available from CORDEX. The black boxes mark the HadGEM2-ES simulations which were used as input for the stakeholder workshops.

For Scotland, almost all models project an increase in temperature as well as precipitation on an annual basis. The projected temperature changes are, however, smaller than for the other case study regions. In summer, most of the models project a decrease in precipitation but about one fourth of the models actually project an increase in Scottish precipitation during summer, even though none of the selected models represent a warmer and wetter summer in Scotland. The models that project the largest increase are not dynamically downscaled in CORDEX. The HadGEM2-ES model simulations nicely represent an intermediate and a high-end change with respect to temperature, annually as well as in summer.

For Hungary, the models agree less well on the projected temperature increase which is between 1–8K on an annual basis and 1–10K in summer. Again, the HadGEM2-ES simulations nicely represent intermediate and high-end temperature change. Especially in summer, the models projecting the largest degree of warming also indicate the largest decrease in precipitation and the HadGEM2-ES model is among the very high-end models in this respect. None of the high-end models project an increase in summer precipitation, so drier and warmer Hungarian summers seem to be a robust signal, at least for the RCP8.5 emission scenario.

For the Iberian Peninsula, warmer and drier conditions annually as well as in summer is a very robust result which almost all models agree on, although the spread is slightly increased in summer. The subset does not include any of the four GCMs with the largest warming, neither annually nor in summer. As none of these locally high-end models have been dynamically downscaled in CORDEX, they could not have been included in the subset even if selection was performed based on regional spread.

For Central Asia, almost all models agree that future climate will be warmer and wetter and that summers will be warmer and drier. For both RCPs, the HadGEM2-ES model is among the models that project the largest warming and the largest reduction in summer precipitation.

Our analysis shows that the selected subset represents the full ensemble relatively well in all the case study regions, when it comes to annual and summer mean changes in temperature and precipitation. However, regional model spread is less well represented when the selection is based on global criteria and a larger number of climate models may be needed in order to represent a sufficient amount of regional model spread. For Scotland none of the selected models represent an increase in mean summer precipitation, even though this is projected by about one fourth of the CMIP5 models.

Our model selection was limited by the decision to use regional climate models for the regional and local case study regions, as this restricted our sample to GCMs which had been downscaled using an RCM. The scatter plots indicate that the model selection was not dramatically limited by this additional requirement, even though CMIP5 models that project slightly higher changes do exist (Figures 5 and 6).

It should be noted, that the subset was selected in order to represent high and intermediate climate change. The subset does not represent the total spread of the full ensemble and the mean of the subset does not necessarily compare well with the mean of the full ensemble. It should also be emphasised that even though the HadGEM2-ES model simulations (RCP4.5 and RCP8.5) nicely represent intermediate and high-end temperature change in all the considered regions, these simulations only represent one climate model and we do not know if this model is more or less realistic with respect to simulating future feedback processes than the remaining ensemble. Furthermore, we did not evaluate the daily statistics or the performance of the model itself.

2.4. Comparing 10 and 30 year averages for the rIAM

Two integrated assessment impact models are applied in the European case study: The IMPRESSIONS Integrated Assessment Platform 2 (IAP2) and the Regional Integrated Assessment Model (rIAM) (see Deliverable D3B.2 [Holman et al., 2017] for further details). For the IMPRESSIONS IAP2, 30-year time slices are used, and the climate scenarios were prepared by averaging the monthly mean climate data over the 30-year periods. For the rIAM, it was decided to use decadal time slices and in order to test to what extent the results would be affected by the choice of temporal resolution, two sets of climate data (10- vs 30-year averages) were prepared for HadGEM2-ES-RCA4. Figure 7 shows comparisons of 10- and 30-year averages for annual changes in temperature and precipitation based on the HadGEM2-ES-RCA4 projections for RCP4.5 (blue) and RCP8.5 (red) for Europe, Hungary, Iberia and Scotland.

The figure shows that even for decadal time slices, the temperature is generally increasing from one time slice to the next, especially for the stronger external forcing (RCP8.5) and for the larger domain (Europe). There are much larger variations for precipitation where natural variability has a stronger impact. Note that this figure shows regional averages, differences between decadal and 30-year averages could easily be larger at the grid point scale.

2.5. Extreme climate indices

To further explore and emphasise the climatic differences between the case study regions and the local responses to high-end global climate change, Figure 8 shows how changes in regional mean temperature and total annual precipitation scale with global mean temperature change in each case study region for the selected subset of models.

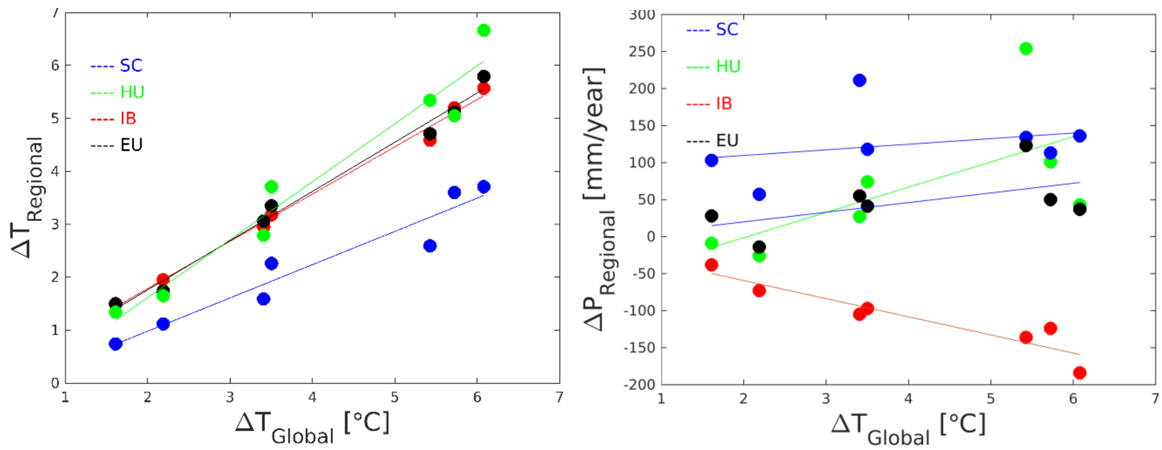


Figure 8: Changes in regional mean temperature (left) and precipitation (right) for each of the case study regions (2071-2100 vs 1981-2010). Temperature data are from the GCMs and precipitation data are from the bias-adjusted RCMs; EU=Europe, SC=Scotland, HU=Hungary, IB=Iberia.

Regional temperature changes scale relatively well with changes in global mean temperature for all case study regions, the spread is slightly larger for Hungary. As also seen previously, regional temperature changes are significantly smaller for Scotland than for the other case study regions.

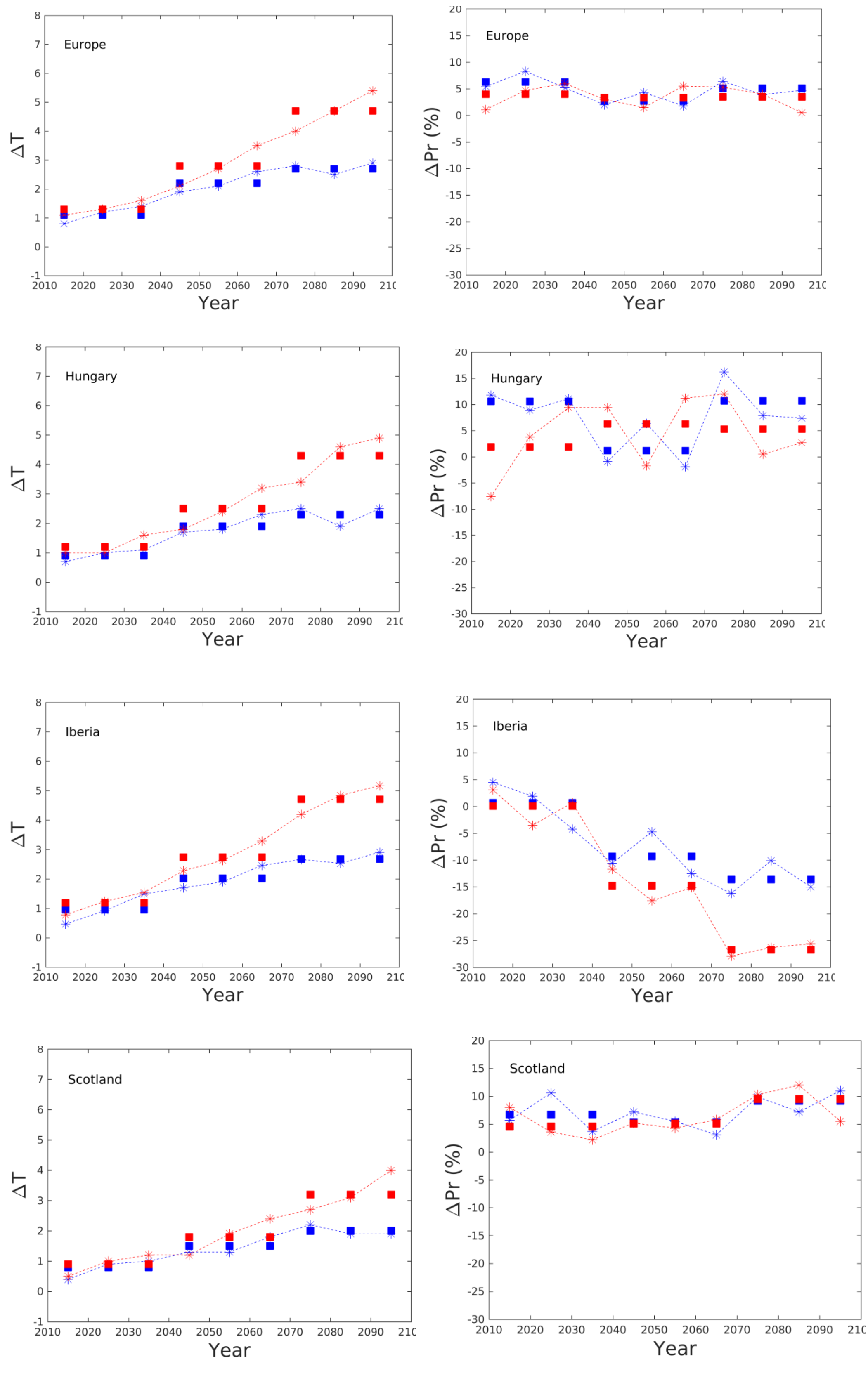


Figure 7: Decadal and 30-year averages of temperature (left column) and precipitation (right column) changes (compared to 1981-2010) for HadGEM2-ES-RCA4 for RCP4.5 (blue) and RCP8.5 (red).

Changes in regional precipitation scale less well with changes in global mean temperature. The best fits are for Europe where averaging is performed for a larger domain, and for Iberia, where annual precipitation decreases for increasing global mean temperatures. For Hungary there is a large difference between the models, especially for the three high-end models.

Figure 9 shows changes in extreme indices: (a) heavy precipitation days (R10mm, annual count of days with precipitation ≥ 10 mm); (b) very heavy precipitation days (R20mm, annual count of days with precipitation ≥ 20 mm); (c) the percentage of total precipitation due to very wet days, R95Ptot; and (d) changes in the longest period of consecutive dry days (CDD). These stress that regional changes are largest for Iberia, and that for this region changes in extreme precipitation indices scale rather well with global mean temperature. For Iberia, there is a large change in the number of consecutive dry days even for the intermediate scenarios, and the selected subset of models does not agree very well on these changes. For Scotland and Hungary, there is an increase in heavy precipitation and a small increase in CDD. For the larger European domain, all indices scale relatively well with global mean temperature (Figure 9).

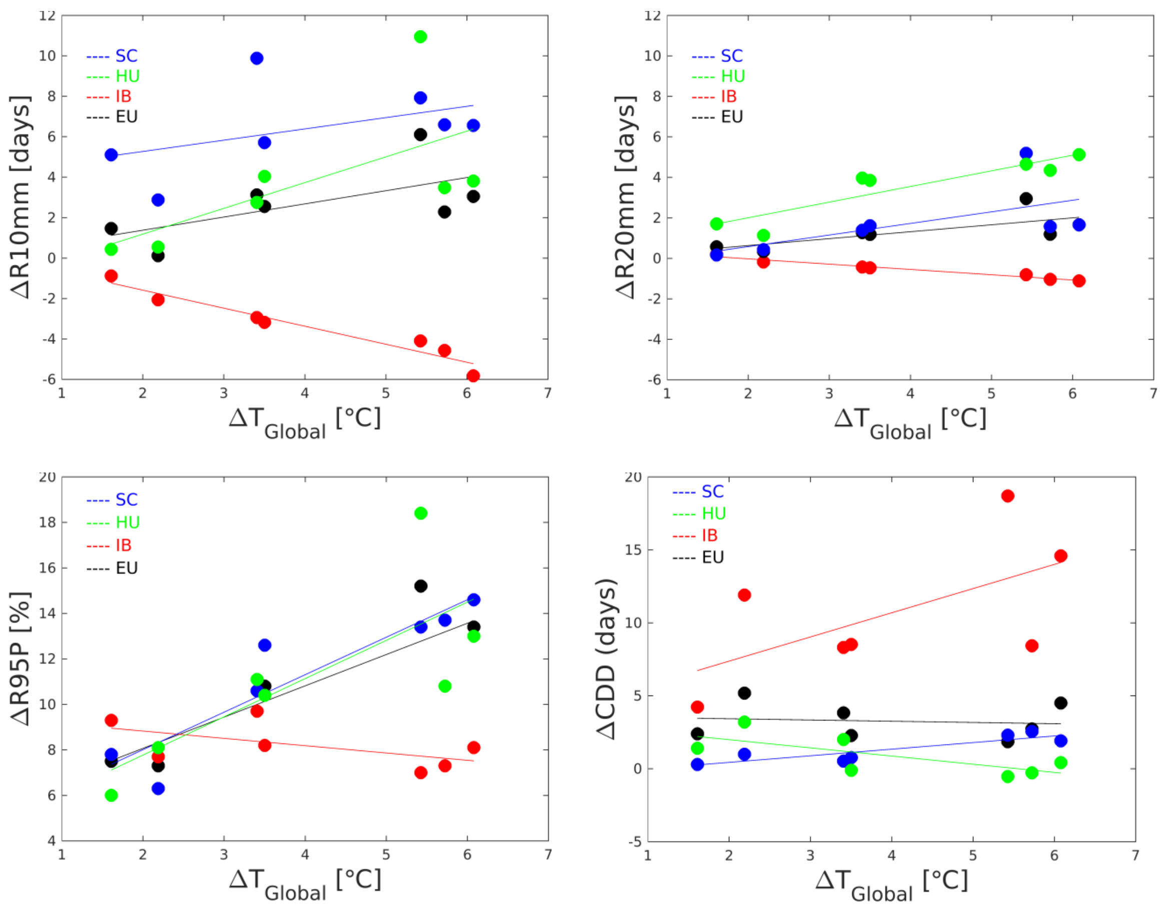


Figure 9: Changes (1981-2010 to 2071-2100) in regional extreme indices as a function of changes in global mean annual temperature. Indices are: heavy precipitation days (R10mm; top left), very heavy precipitation days (R20mm; top right), percentage of total precipitation due to very wet days (R95Ptot; bottom left) and changes in the length the longest period of consecutive dry days (CDD; bottom right).

2.6. Climatic tipping elements

A number of climate system components may possess a critical threshold beyond which transitions to a different state occurs. Lenton et al. (2008) introduced the term tipping element for large-scale subsystems of the Earth system that can be switched – under certain circumstances – into a qualitatively different state by small perturbations. Following this definition, a tipping point is the critical point at which the future state of the system is qualitatively altered. Some tipping point transitions cause abrupt and irreversible changes, but for slower processes gradual changes may occur. Potential climate tipping elements include the Atlantic Meridional Overturning Circulation (AMOC), Arctic sea ice, the Greenland and Antarctic Ice Sheets, the Amazon forests, and monsoonal circulations.

Figure 10 illustrates the range of global mean temperature change at which the tipping points of a number of main tipping elements may occur. There is a large uncertainty related to the tipping points of each tipping element, especially for tipping points expected to occur at high levels of global warming. Some of these tipping elements may already be affected by the present state of global warming and several tipping points may be reached even if global warming is limited to below 2°C.

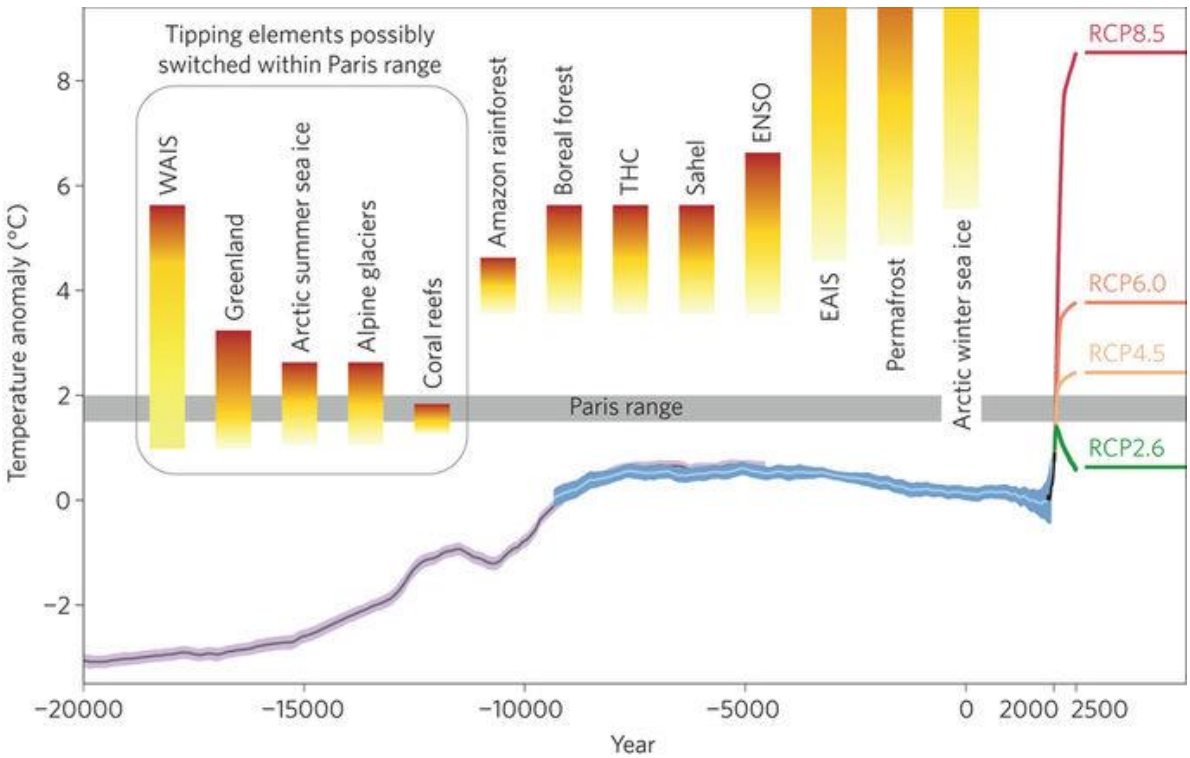


Figure 10: Ranges for crossing a number of large scale tipping points (Figure from Schellnhuber et al., 2016). WAIS=West Antarctic Ice Sheet; THC=Thermohaline Circulation; ENSO= El Niño–Southern Oscillation; EAIS=East Antarctic Ice Sheet.

Global climate models may not include all the feedback processes that would be necessary to model the occurrence of a given tipping point. For instance, most GCMs assume a stable Greenland Ice Sheet and do not include the feedback mechanisms (e.g. responsive surface albedo) that would allow for accelerated melting of the ice sheet. In the same way better dynamic vegetation schemes would be needed in order to assess the influence of local and regional feedbacks to, for example, long-term droughts. Abrupt changes in the climate system are therefore difficult to assess and the timing of these changes is very difficult to predict.

Tipping elements may also have different impacts on the climate system. Changes in sea-ice and permafrost affect global warming via changes in albedo and greenhouse gases. Changes in the AMOC or Arctic sea ice cause regional changes in temperature and precipitation, and melting ice sheets causes the sea level to rise. Gradual climatic changes, like gradual increases in extreme events, may also have impacts that are comparable with those of tipping points.

Climate tipping points are traditionally defined as large scale events, but it seems possible that local scale tipping points may add up to have global effects and that multiple interacting tipping points could have rather unknown implications - this could be the combination of extended droughts and a very strong heat wave or it could be the mutual interaction between abrupt societal and climate changes.

Presently, there is a very low level of agreement between climate models when it comes to tipping points and abrupt changes (Drijfhout et al., 2015) and the effects of climatic tipping points cannot be expected to evolve from state-of-the art climate modelling.

3. Analysis of socio-economic scenarios

Socio-economic scenarios (SSPs) were developed for all five case studies. Deliverable D2.2 (Kok and Pedde, 2016) provided an overview of the main SSP-related products for all case studies and all SSPs. The deliverable also presented an initial comparison of SSPs across case studies, which we build upon here. This section starts with an overview of all scenarios developed in the case studies.

Figure 11 shows the cross-scale scenario development design for the five case studies of IMPRESSIONS. In general, the global SSPs were used to contextualise the SSP development in all case studies, except Europe. The European SSPs were based on a more closely linked downscaling of the global SSPs. For details, see Kok et al (in review).

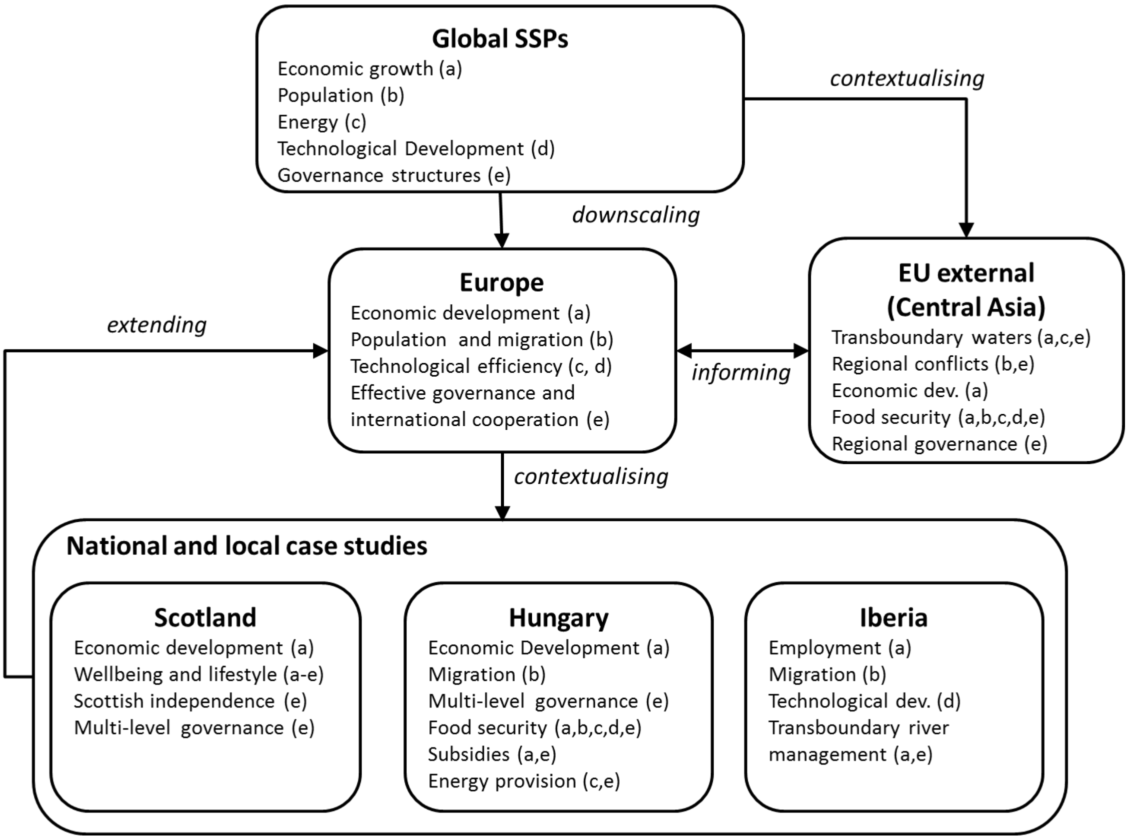


Figure 11: Schematic representation of cross-scale scenario development design for the five case studies in IMPRESSIONS. For every case study, an indication is given of the most important elements: (a) economic development; (b) demography; (c) infrastructure; (d) technology development; (e) governance structure.

In all case studies, the SSPs consisted of multiple products, three of which were developed in all case studies (Kok et al., in review):

1. **Narratives**. Stories of about 500 to 1500 words were constructed to sketch the main development in three times slices between 2010 and 2100.
2. Overview of **key (story) elements**. Tables with 10 to 15 additional key (story) elements were constructed to provide a quick overview of main developments across scenarios and additional qualitative information.

3. Overview of **trends of key (model) variables and quantified Fuzzy Sets.** Tables with trends of 8 to 15 model variables that were partly quantified using Fuzzy Sets. This includes estimates of changes in human, social, manufactured and financial capital for all case studies.

Below, a short overview and analysis of some aspects of the narratives and key story elements is provided.

3.1. Overview of narratives and qualitative elements

Table 3 shows the names given to the SSP narratives in the various case studies. This gives a flavour of how global developments were perceived to be playing out at more local scales. SSP1, Sustainability, was mostly seen as a (very) rosy future outlook where all problems would be solved, which is reflected in names such as "Pink Dream" or "MacTopia". SSP3, Regional Rivalry, was regarded as the opposite: a dark, gloomy future where most problems worsen, hence names such as "Icarus" and "Mad Max". The interpretation of SSP4, Inequality, was less uniform, following the basic logic of an unequal society, but with versions where social uprise cannot be avoided ("Tartan Spring") or where the elites have power struggles ("A Game of Elites"). SSP5, locally, was often interpreted as a somewhat negative future outlook due to widespread environmental destruction. However, in the case of Europe and Scotland, the emphasis was on human capital development and economic redistribution through markets and technology that co-exist with environmental degradation until 2100. This is reflected in the Scottish SSP5 name "Techadonia".

Table 3: Overview and names of SSPs developed in all case studies of IMPRESSIONS.

Case study	SSP1	SSP3	SSP4	SSP5
Global	Sustainability	Regional Rivalry	Inequality	Fossil-fuelled development
Europe	We are the world	Icarus	Riders on the storm	Fossil fuelled development
Scotland	MacTopia	Mad Max	Tartan Spring	Techadonia
Iberia	Sustainability	Regional Rivalry	Inequality	Fossil-fuelled development
Hungary	Roszasim alom (Pink Dream)	Regional Rivalry	Inequality	Pató Pál Úr (Mr. Pál Pató)
Central Asia (EUx)	Sustainability	Regional Rivalry	A game of elites	Fossil fuelled development

Table 4 present an overview of other key elements in all case studies. Some observations are:

- Key elements for Europe and Scotland were derived from those used in an earlier project (CLIMSAVE), and these were matched with the selection of global key elements in an expert workshop. There is thus a very close link with the global elements by design.
- In general, the more local the case study, the larger the difference with the global elements. Also, local case studies tended to produce tables of key elements that were smaller, and additional information that was more in narrative form. Narratives tended to be longer, which partly explains the lack of tabular data.
- In general, case studies with less modelling activities tended to have less elaborate tables of key elements. An important use of tabular information was to help parameterise models.

- There is a small but important set of elements that was considered in all case studies, and that is instrumental in the cross-scale comparison. This list includes international cooperation, population and migration, economic development, energy (production), and geopolitical stability.

Table 4: Overview of key elements as determined in all case studies of IMPRESSIONS.

Global SSP element	Europe	Scotland	Iberia	Hungary	Central Asia
Institutions	Decision-making level	Decision-making level			
Institutions and international cooperation	Geopolitical stability	Geopolitical stability	Coordination		Military conflicts
International cooperation	International cooperation	International cooperation	Multi-level decision making	International trade	Water-sharing agreements
Societal participation	Social respect	Social respect	Public participation		
Population growth/ migration	Net migration	Net migration	Population and migration – urban dynamics	Population	Population movements
Economic growth	Economic development	Economic development	Economic growth and job creation	Finance and economic development	Economic development
Migration	Mobility	Mobility			Population movements
Globalisation	Globalisation	Globalisation			
Policies	Choice	Choice			
Social cohesion	Social cohesion	Social cohesion	Social innovation		
Technology development	Technology development	Technology development	Technology development		Technology
Policy orientation	Quality of Governance	Quality of Governance	Governance	Government and management	
Health investments	Human health investments	Human health investments		Health	
Education	Education investments	Education investments			
Environmental policy	Environmental respect	Environmental respect	Energy production	Energy	Energy production
				Land use and agriculture	Food security
				Water use	

We also analysed the trends of key elements across all scenarios in all case studies. To illustrate, we present the results for two scenarios, SSP1 and SSP4.

For SSP1, trends in all case studies indicate a strong and effective multi-level governance in a world with less barriers. Public participation is strong and growing, also stimulated by governments that focus on sustainability. Health investments are high and the focus on energy is on renewables. Population movements in some case studies are assumed to be low, as most people are happy where they are. Yet, in Iberia a repopulation of the countryside is assumed, while in Central Asia people continue to move away from the region. Overall, economic development is assumed to be gradual. Yet, in Iberia, Hungary and Central Asia stronger growth is assumed, which is needed to “catch up”.

For SSP4, trends in all case studies relate to an increasing inequality with a focus on the establishment of elites, an increasing emphasis on green technology development, and more renewables. Overall, there are important differences for two elements, population movements and economic growth. The case studies show that the general trends for Europe as a whole obscure the fact that there are winners and losers in SSP4.

3.2. Cross-scale analysis of SSPs

This section brings together the bulk of the research that has been undertaken on socio-economic scenarios within WP2 to analyse the scenarios across scale. Section 3.2.1 reports on the cross-scale analysis of the SSPs when used to contextualise normative pathway construction. Section 3.2.2 analyses the qualitative stories and the worldviews they represent across case studies. Section 3.2.3 analyses quantitative model input and output related to a key model parameter. Together, these analyses aim to highlight key cross-scale differences and similarities, as context for pathway construction (in WP4), as model input (in WP3), and as a stand-alone (qualitative) product.

3.2.1. Cross-scale analysis of the potential for mitigation, adaptation and transformation

This section (based on Pedde et al., in review) analyses the potential for mitigation and adaptation within each SSP across case studies. This has been done by identifying the elements that ‘enable’ climate action in each SSP through an assessment of: (i) the five capital stocks available for society to draw upon (human, social, natural, financial and manufactured capital); and (ii) the four capacities that enable change to take place through leveraging and being able to access these capitals (stewarding, unlocking, transformative and orchestrating).

The overall methodology builds on the SSP×RCP framework to identify how different SSP×RCP combinations enable or constrain the achievement of the vision of a sustainable future in 2100 for each case study, as co-developed with stakeholders in WP4. Achieving the vision requires strong and integrated climate change adaptation and mitigation action, involving not just technological development but also institutional change, behavioural change and land use change, consistent with the level reported in integrated assessments globally (Riahi et al., 2017) and regionally (van der Zwaan et al., 2016). It thus requires societal transformation, defined as “a major, fundamental change, as opposed to minor, marginal, or incremental change” (Feola, 2015). Here, we assume that such transformation is desirable (Hermwille, 2016; Westley et al., 2011).

The analysis builds on the standpoint that people are the solution to modifying human and natural systems to tackle climate change (O'Brien, 2015; O'Brien, 2016). Thus, the first step is to identify which stocks of capital (Deliverable 2.2) can be mobilised by the actors in each integrated scenario. In this methodology, we define actors as individuals or organisations with the capacity to act within the social structures and change the state of human and natural systems (O'Brien, 2015). Actors are categorised to represent different levels of aggregation and sectors (Avelino and Wittmayer, 2016): governments, communities, markets and research. The role played by the actors is systematically analysed by assessing their capacities to act (Hölscher, 2018a) and determines whether and how the capital stocks can be mobilised (Gillard et al., 2016). To develop and implement mitigation and transformation strategies and actions, different types of capacities are needed (Hölscher, 2018b). Capacities determine the potentials of actors in the scenarios to effectively mobilise capital stocks in the strategies and actions and thus, in turn, change the capitals.

The conceptualisation of the capacities builds on a review of different literatures that are concerned with studying and analysing agency in relation to (transformative) change in societal systems, namely sustainability transitions literature (Grin et al., 2010; Loorbach et al., 2015) and resilience approaches (Folke et al., 2010; Olsson et al., 2014; Westley et al., 2013). We conceptualise four capacities: stewarding, unlocking, transformative and orchestrating. First, stewarding capacity enables learning and self-organisation to protect people and infrastructures from the impacts of socio-economic and climate change and build resilience (Chapin et al., 2010; Chelleri et al., 2015; Folke et al., 2010). Second, unlocking capacity enables dominant regimes of production and consumption to be destabilised and rigid structures to be loosened and changed so as to prevent path-dependencies and maladaptation in existing societal development pathways (Geels, 2014; Kivimaa and Kern, 2016; Loorbach, 2014). Third, transformative capacity enables the creation of fundamentally new types of solutions, practices and approaches and embedding of these in new structures, cultures and practices (Frantzeskaki et al., 2012; Kivimaa et al., 2017; Rauschmayer et al., 2015; Westley et al., 2013). Fourth, orchestrating capacity enables the multiplicity of actors and actions to be aligned and co-ordinated to achieve synergies and avoid trade-offs across scales, sectors and time in line with a long-term vision (Abbott et al., 2015; Chan et al., 2015; Frantzeskaki et al., 2014; Hodson and Marvin, 2010).

Three levels of capacity were defined through expert interpretation and synthesis of the literature review by the IMPRESSIONS' team (WP2 and WP4) to match the three levels of capitals (low-medium-high) assessed as part of the participatory scenario development process in each case study.

This framework facilitates the integration of human and societal dimensions of agency (via the capacities) into the quantitative analysis of mitigation and transformation. The crucial point in the framework is that the level of societal transformation required to meet the vision cannot be achieved through only one type of action (e.g. technological action alone) due to spillovers and trade-offs (IPCC, 2014). According to this reasoning, mobilising capital stocks to enable the full spectrum of mitigation and adaptation activities requires all four types of capacity. However, the societal context (i.e. the SSP×RCP integrated scenario) determines which capacities and which type of action will be enabled.

In all case studies, SSP1 achieves the highest capitals and capacities because of the active participation of all actors (market, research, government and third sector) towards sustainability. In the European SSP1, strong international cooperation and institutions, most importantly the political integration of European countries in view of shared sustainability priorities, enable the establishment of multi-level governance and an early shift towards a sustainability focus. European institutions also play a positive role in enabling a strong early push towards sustainability in the Hungarian and Iberian SSP1 (the European Union in Hungary and a "European social framework" in Iberia), in combination with bottom-up social participation and municipality-level sustainability-oriented investments and governance. Only in the Scottish SSP1 is the trigger towards sustainability not directly enabled by the European Union but rather by the Scottish government and society.

The quick transition towards sustainability in SSP1 leads to the maintenance and further steady creation of capacities until 2100. Societal and environmental awareness is generated early in the scenario, resulting in high levels of human and social capital and thus in high orchestrating, transformative and stewarding capacity. The unlocking capacity that has supported the establishment of the other capacities decreases towards 2100 as the new sustainability paradigm is established and the importance of opposition networks decreases. Therefore, SSP1 in all case studies gets close to but does not reach the vision, in spite of the very high potential for mitigation and transformation since the beginning.

In SSP3, capacities and capitals move downwards in all case studies. The cause of the overall decrease of capacities is the focus on the short-term governance, low innovation and investments for leadership. The lack of reflexivity and learning from tested solutions results in generally low stewarding, transformative and orchestrating capacities, apart from in Scotland. In Scotland, governance and innovation is managed by large companies.

In SSP4, capacities tend to average out at a medium level for two reasons: overall competition and a combination of high capacity for local actors with low capacity for actors at the national or European level. In Europe, Iberia and Scotland, powerful multinationals exert a stabilising influence which enables cooperation (orchestrating capacity) and innovation (transformative capacity), although learning is limited due to competition, political and economic power grabbing and large-scale social exclusion. In Hungary, social networks and reflexive learning, together with the existence of counter-movements until 2070, generate high stewarding and unlocking capacity in communities. At the national level, however, the focus is on coping, low investments, and rigid top-down maintenance of status throughout the whole scenario, *de facto* decreasing the potential of local actors.

SSP5 has the most diverse level of capitals and capacities of all scenarios. Natural capital is low in all SSP5 case studies, but human and social capital are high in Europe and Iberia but low in Scotland and Hungary. Although all SSP5 case studies share the common traits of economic development and social equality, the effect of the environmental damage of SSP5 was perceived differently. Capacities range from low to high, with the lowest capacities being in Iberia and Hungary. All local case studies end up with high unlocking capacity, consistent with lack of support for the status-quo and effective opposition. Because other capacities and/or capitals are limited, overall potential remains close to "medium", except for Europe where potential is "high" due to the availability of knowledge, capitals, technology and preparedness to shift to "re-emergence of investments in renewables" when needed.

Figure 12 shows the overall potential of the SSPs analysed in the four case studies to transform societies to live consistently with the vision. As explained in the theoretical framework, this depends on the capacities of actors to mobilise all the capitals. Letters representing each of the four capacities are plotted on a scale of high-medium-low. The intensity of shades of green of the boxes indicates how these levels of capitals and capacities combine to determine society's potential to achieve the vision in each scenario. For example, in the European SSP1 the potential for achieving the vision is "very high" as a result of "high" social and human capitals and "high" stewarding, orchestrative and transformative capacity, whereas the European SSP3 results in "low" potential because of overall "low" capitals, "low" stewarding and orchestrating capacity, "medium" transformative capacity, and "high" unlocking capacity.

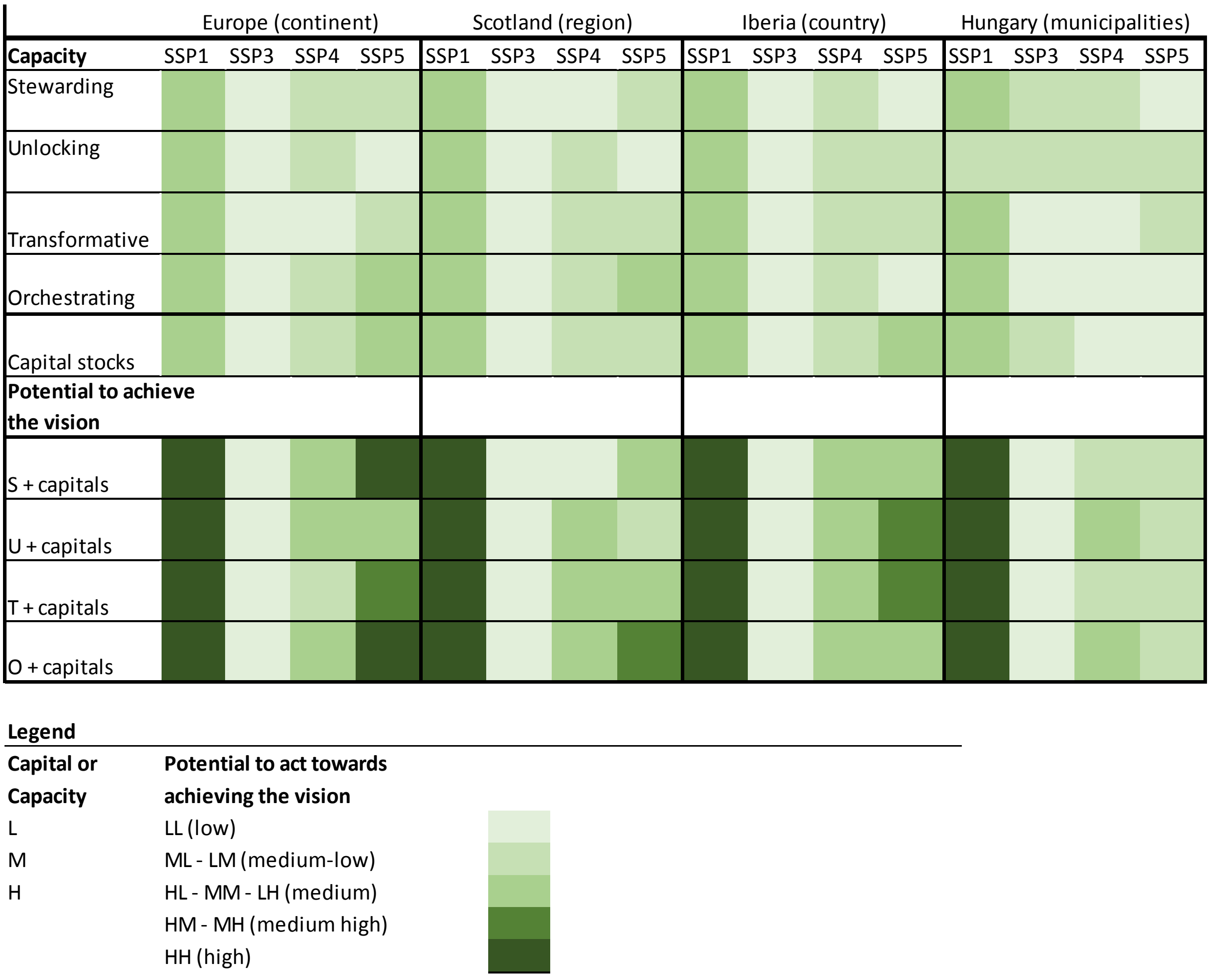


Figure 12: Analysis of the potential to transform society to function consistently with the requirements to achieve the vision for each SSP×RCP integrated scenario as a result of the combination of different levels of capitals and capacities in each case study in 2100. The capacities assessed are stewarding (ST), unlocking (UN), transformative (TR) and orchestrating (OR). Adapted from Pedde et al. (in review).

Because of the high levels of both capacities and capitals, SSP1 has generally "very high" potential to transform (except that the "medium" unlocking capacity restricts potential to "high"). In contrast, SSP3 has "very low" or "low" potential in all case studies, as the capitals and capacities are low due to the power of the Haves coupled with conflicts and disparities. However the unlocking capacity can become higher, in scenarios where communities of interest are established. This provides some stability and decreases conflict, albeit with larger inequalities than at present. In the European SSP3, the European Union collapses but "richer (ex) Member States" can still afford clean technology, clean water, energy and health services. In the Scottish SSP3, the have-nots organise themselves.

SSP4 tends to have "low" or "medium" potential across all case studies. This is because cohesion, collaboration and networks exist within social classes (unlike the more conflictual SSP3 scenarios). However, stratification and social exclusion limit the capitals and capacities, and thus the overall potential. Despite generally having higher capitals than SSP3, due to more stability and economic growth, the overall potential of SSP4 is similar to or only slightly higher than SSP3 because the capacities tend to change little throughout the scenario.

The potential to transform in SSP5, in contrast, ranges from “very low” to “very high”. For example, in Europe and Scotland high stewarding and transformative capacity are available, as risk-taking and uncertainty are embraced and innovation is embedded. However, the lack of engaged political culture tends to reduce the potential in all case studies. A U-turn towards sustainability emerges in all SSP5 case studies by 2100, but this happens smoothly in Europe and Scotland whereas in Hungary and Iberia, with lower transformative potential, the transition is much more chaotic.

This assessment of capitals and capacities for each scenario can complement the use of Integrated Assessment Models (IAMs) by adding a ‘human’ element to the analysis. Our framework can provide a ‘reality check’ to indicate whether the societal conditions envisaged within each SSP would actually allow the relevant actors to build and mobilise the capitals that are required to implement the mitigation options to meet a given RCP.

3.2.2. Cross-scale analysis of the SSP narratives using scenario archetypes

The worldviews present in the scenario narratives were analysed to identify whether and how perspectives change within and across scenarios and/or case studies. The methodology builds on the application of Cultural Theory (Boschetti et al., 2016) as a systematic tool to classify qualitative SSP narratives within multi-scale scenario development. It also builds upon the well-established assumption that existing scenarios tend to fall within archetypes (Hunt et al., 2012).

The starting point consists of the SSP global narratives which have a clear direction at the global level in socio-economic, technological, institutional and environmental trends. SSP1 is a sustainable scenario with effective collaboration across all actors of society, SSP3 is a socially fragmented and environmentally challenging scenario, SSP4 is a high-tech, green, effective institutionally and internationally scenario but with high inequality across and within society, and SSP5 is a fossil fuel, market- driven and reduced-inequality scenario. If mapped against scenario archetypes, the global SSPs match very well onto four of the Global Scenario Group archetypes: “Great Transitions” with SSP1, “Barbarisation” with SSP3, “Conventional-Policy-Reform” with SSP4 and “Conventional-Market-Force” with SSP5 (Hunt et al., 2012; Raskin, 2005). The main diverging match is SSP4 and Policy Reform. Even if they both assume strong government-led policies to achieve sustainability, the main difference is the interpretation of how such top-down policy approaches fare in society. Whereas Policy Reform assumes that social equity is an integral part of sustainability policy (Hunt et al., 2012), SSP4 includes a narrative for those excluded resulting in a dualistic scenario of effective international cooperation in a socially unequal world (O’Neill et al., 2017).

The scenario narratives for the European, Scottish, Iberian and Hungarian SSPs were analysed using “narrative coding” (Offermans and Cörvers, 2012). This involved analysing the text to identify dominant perspectives taken as framed in Cultural Theory (Thompson et al., 1990; see Box 1).

BOX 1: Four ways of life according to Cultural Theory.

Source: http://changingminds.org/explanations/culture/grid-group_culture.htm

<table>
<tr>
<td>Fatalism: The fatalist culture has differences between, yet limited bonding between, people. A result of this is that those who ‘have’ feel little obligation towards the 'have nots'. Individuals are left to their own fates, which may be positive or negative for them. They thus may become apathetic, neither helping others nor themselves. Those that succeed, however, feel they have done so on their own merits and effectively need those who are less successful as a contrast that proves this point.
Also known as: Isolate
Style: Apathy, avoidance
Nature as: Capricious, uncertain
Risk view: Danger, no gain
Key: Power imbalance
Cultural hero: none
Leadership: Despotic
Manage needs? : No
Manage resources? : No</td>
<td>Hierarchism: In a collectivist culture, people are strongly connected yet are very different. This leads to the development of institutions, hierarchies and laws that both regulate individual action and provide for weaker social members. Within overall collectivist hierarchies, other sub-cultures may survive, for example in a national collectivist model there may be egalitarian or individualist groups who, whilst generally obeying national laws, will have differing internal rules.
Also known as: Positional, Hierarchical
Style: Hierarchy
Nature as: Robust, to a point
Risk view: Managed
Key: Obedience
Cultural hero: Bureaucrat
Leadership: Positional
Manage needs? : No
Manage resources? : Yes</td>
</tr>
<tr>
<td>Individualism: In an individualistic culture, people are relatively similar yet have little obligation to one another. People enjoy their differences more than their similarities and seek to avoid central authority. Self-regulation is a critical principle here, as if one person takes advantage of others then power differences arise and a fatalistic culture would develop.
Also known as: Markets
Style: Competition, Lassez faire, Pragmatic materialism
Nature as: Benign, robust
Risk view: Opportunity
Key: Self-regulation
Cultural hero: Pioneer
Leadership: Meteoric
Manage needs? : Yes
Manage resources? : Yes</td>
<td>Egalitarianism: In an egalitarian culture, there is less central rule than in collectivism, but this requires individuals to voluntarily help others. The rule is thus less about law and more about values. External laws may be seen as necessary only when there is weakness of character, which is prized highly. The fact that people are essentially similar leads people to agree and adopt similar values. This is an ideal utopia and while it may survive in smaller groups, national egalitarian cultures are rare, if any exist. To survive this requires that if one person breaks values, all others turn on this person, correcting or ejecting them.
Also known as: Enclave, Communitarian, Sectarianism
Style: Equality, commune
Nature as: Ephemeral, fragile
Risk view: Delicate balance
Key: Integrity
Cultural hero: Holy person
Leadership: Charismatic
Manage needs? : Yes
Manage resources? : No</td>
</tr>
</table>

The text is then colour-coded to highlight those lines associated with each worldview (see excerpt of coding from the Scottish SSP1 – Mactopia narrative; Figure 13). The number of lines are then summed for each worldview and assigned a percentage of the total narrative.

empowerment and more bottom-up decision making. It also makes teleworking possible and increases the levels of access to information for all residents of Scotland. Many of the transitions towards an equitable and sustainable society require effective regulation from the government. The presence of the government increases at all levels, but does not become centralised. Efficient use of resources, circular economy and economy at the local level contribute to a sustainable, environmentally aware economy. The economy is diversified (diversified business environment) and attracts businesses. By the same token, harsh penalties are dealt out to those households not switching to renewable energy sources. Some pockets of the population do not agree with the

Figure 13: Excerpt from the Scottish SPP1 narrative, showing narrative coding according to Cultural Theory.

The results from the narrative coding are shown in Figures 14 and 15. SSP1 tends be located in the upper left quadrant (i.e. combining egalitarian and hierarchic worldviews), with Iberia being the most egalitarian. SSP3, while being always in the lower fatalist quadrants, tends to fluctuate between combinations with egalitarianism (Iberia and Hungary), individualism (Europe) or both (Scotland).

SSP4 is distributed across all quadrants: hierarchic and individualist in Europe; hierarchic, hierarchic-egalitarian and egalitarian hierarchic in Iberia; hierarchic-individualist, individualist-fatalist, fatalist-egalitarian in Scotland; hierarchic-individualist, and fatalist-egalitarian in Hungary (Figure 15). The fatalist-egalitarian perspective is dominant and visible in all local case studies as a result of perceived top-down enforcement and strongly hierarchist governance components. Interestingly, this perspective is less visible in the European case study, where only the hierarchic component is visible with individualist elements.

Lastly, SSP5 tends to be in the hierarchic-individualist quadrant, typical of the “capitalist” culture, at least in the first time slices. However, in the Iberian and Hungarian case studies, the last time slice tends to move towards fatalist-egalitarian worldviews, which are reflected in the narratives where a powerless society is faced with a necessary transition from fossil fuels to sustainability and a change in environmental awareness.

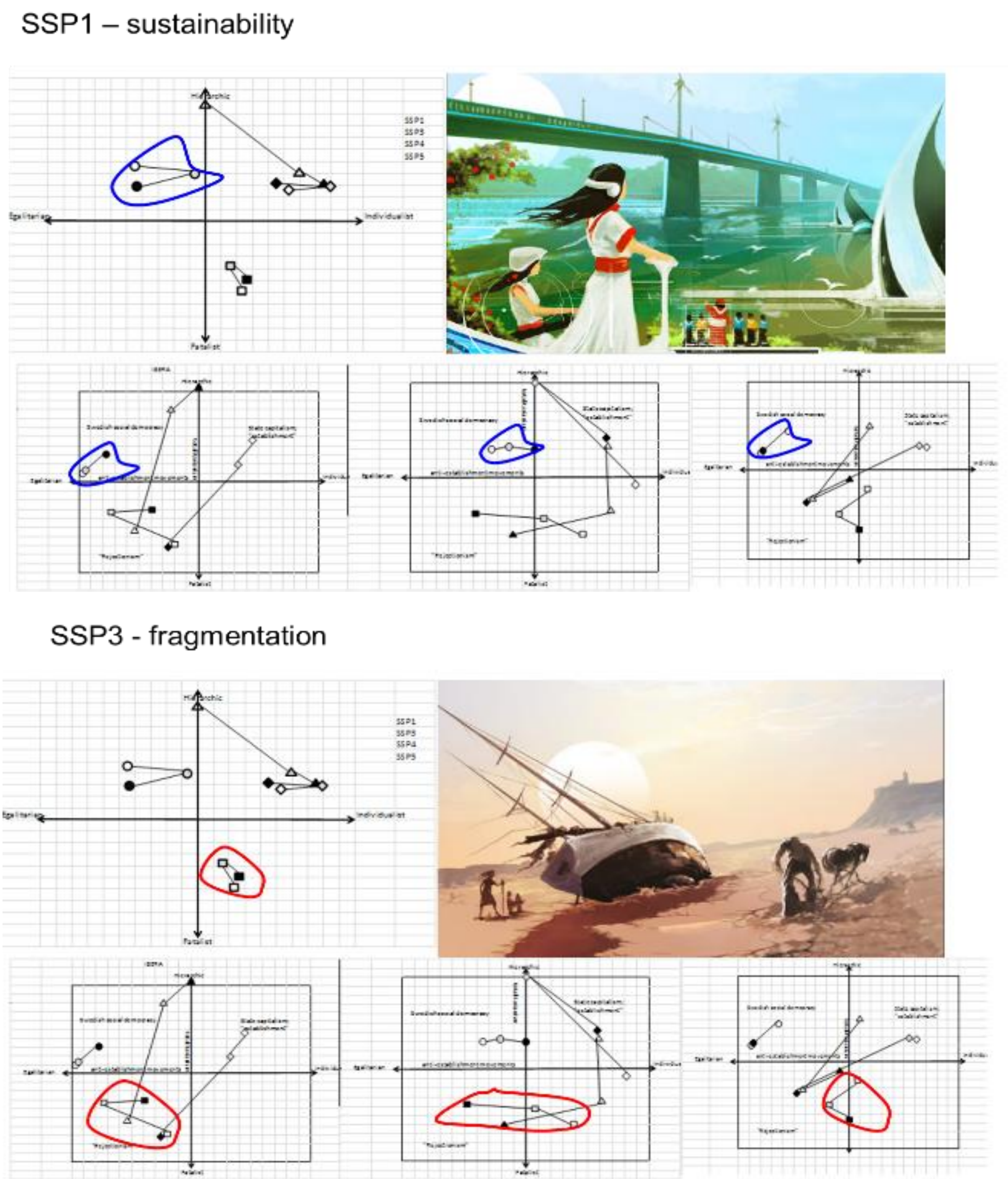
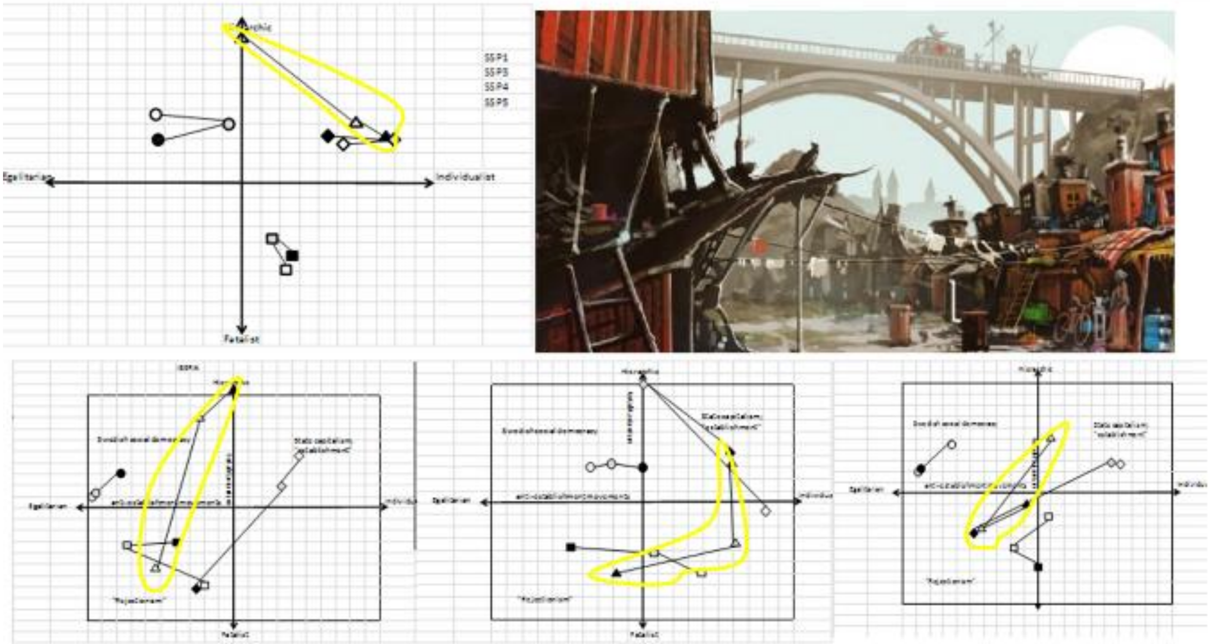


Figure 14: Combinations of worldviews across case studies in SSP1 (blue circles) and SSP3 (red circles). The top left quadrant shows evolving worldviews in Europe, and the lower three figures the worldviews in Iberia (left), Scotland (middle) and Hungary (right). Axes polarities: North=hierarchism, South=fatalist, East=individualist, West=egalitarian.

SSP4 – green tech but social inequality



SSP5 – market-driven scenario

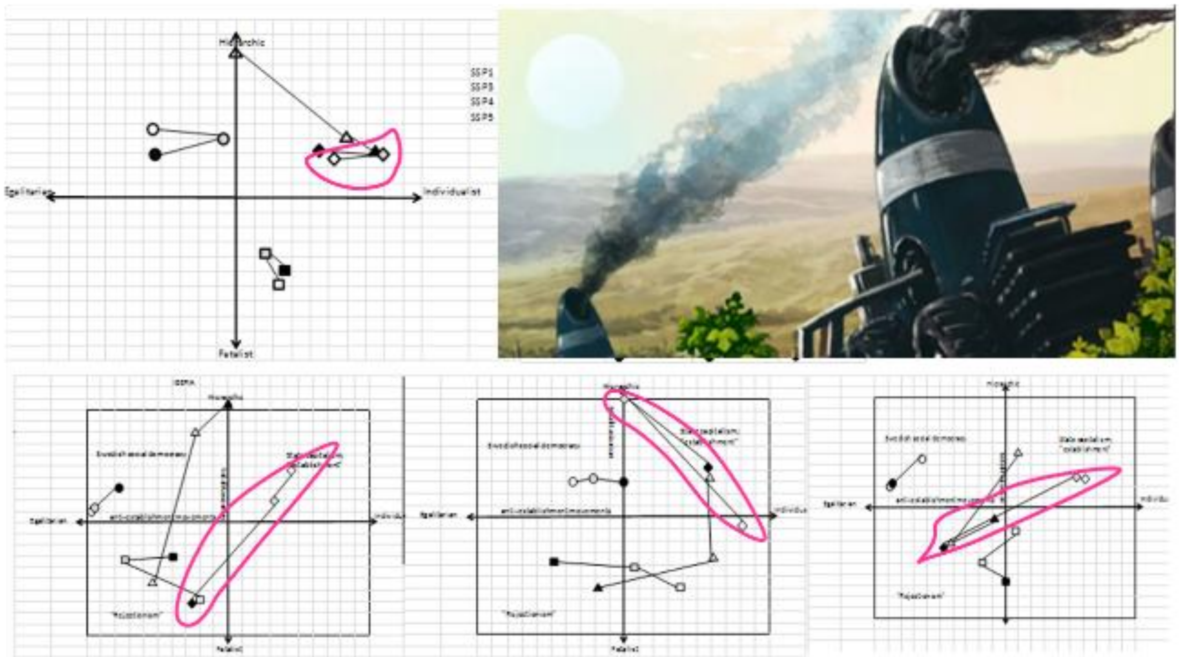


Figure 15: Combinations of worldviews across case studies in SSP4 (yellow circles) and SSP5 (pink circles). The top left quadrant shows evolving worldviews in Europe, and the lower three figures the worldviews in Iberia (left), Scotland (middle) and Hungary (right). Axes polarities: North=hierarchism, South=fatalist, East=individualist, West=egalitarian.

3.2.3. Cross-scale analysis of population dynamics in the SSPs

Population is one of the key variables in socio-economic scenario modelling across all case studies in IMPRESSIONS. In this section, we focus on the case of urbanisation modelling because of its links to population structure (Carter et al., 2016; Terama et al., 2017). Demographic change and future urbanisation trends must be analysed in their local (national to sub-national) socio-economic contexts. For instance, urban sprawl is directly related to both a changing population structure (i.e. the total population and its age profile) and societal preferences, as predicted by the GDP and capital trends in the socio-economic scenario, in regard to the residential preferences of the population and planning legislation. With this analysis we highlight where caution is required when interpreting downscaled results. Assumptions inherent in global scale scenarios influence regional scale models in perhaps surprising ways.

Demographic trends are used as an input to the Regional Urbanisation Growth model version 2 (RUG2; see Deliverable D3B.2 [Holman et al., 2017] for further information). Demographic drivers within the RUG2 model are: (i) consistent with the global trends of population and spatial planning quantified at the national scale (Jiang and O'Neill, 2017; KC and Lutz, 2016); and (ii) influenced by the European SSP narratives. These European SSP narratives were enriched with context specific "urbanisation narratives," describing artificial surface expansion driven by changes in total population, population structure, societal preferences and spatial planning. The direction of these drivers are summarised in the urbanisation narratives of the European SSPs.

The RUG2 model is based on a coherent "top-down" modelling approach, from global to European scales. This analysis focuses on identifying qualitative information from the local and European SSP narratives on population, mobility and urbanisation trends to discuss similarities and differences with the key driving forces and their relevance for the RUG2 European scale urbanisation modelling. Key parameters in RUG2 are the total population, age and life-cycle stage, residential preferences and planning (Terama et al., 2017). Fundamental to the residential preference parameterisation in RUG2 is the concept that life-cycle stage influences the residential preferences of individuals/households. To this end, RUG2 further distributes the population of each region across a set of preferred residential types in a 10' grid across Europe. Preferences can represent a choice driven by an attraction for a given residential type, or an enforced residential selection which is required (by the population) to satisfy a need (for jobs or access to social services). Preferred residential types are defined as a function of age-group, the scenario being considered, and a baseline (region specific) description of the population's residential preferences. In summary, RUG2 is influenced by assumptions at the global scale through the global SSP quantification of population growth, at the European scale through the parameterisation of European narratives preferences connected to socio-economic factors, such as poverty and lifestyles, and at the national scale through assumptions related to fertility and migration. Coherence across these assumptions was tested by first looking at the European broadscale modelling results and then by analysing these trends against local scale narratives.

At the European scale, the greatest artificial surface expansion (AS) is observed in SSP5, which increases by 150% compared to the current area of artificial surfaces of about 16.7 million ha. This development could be classified as urban sprawl (Terama et al. 2017), and is a clear characteristic of the SSP5 socio-economic scenario assumption in which a growing, individualistic society with increasing wealth seek the larger properties and lower population densities associated with suburban, town and rural areas. In this scenario, market logic prevails, driving urbanisation as the most preferable and profitable pathway for development. The artificial surface demands of an expanding population are further magnified by a shift towards expansive residential types.

Contrasting the urban sprawl of SSP5 are those socio-economic scenarios which promote migration to, and densification of, cities. Both SSP1 and SSP4 are characterised by limited artificial surface increases by 2100, compared to the baseline, with a 10% increase for SSP1 and a 5% increase for SSP4. However, the mechanisms of this change differ significantly between the scenarios. Within SSP1 an increasingly environmentally aware society values sustainable urban development and a shift towards more compact, high density living; a shift that mitigates substantive artificial surface expansion. Urban centres within this socio-economic scenario are vibrant, attractive, environmentally-friendly residential areas. These vibrant, attractive urban centres are in stark contrast to the urban ghettos predicted for SSP4. Within this socio-economic scenario, urban living is driven not by societal preferences, but in response to a poorer society moving to urban centres in search of jobs and social services. This urbanisation combined with a declining population limits artificial surface expansion within this socio-economic scenario even more than the SSP1 scenario.

The intermediate artificial surface expansion of SSP3 is driven by urban migration and countryside abandonment. In contrast to the 'urban ghettos' of SSP4, however, urbanisation in SSP3 is focused on suburban (peri-urban) areas, i.e. regions that have a larger artificial surface 'footprint' than more densely populated city centres. As a consequence, more artificial surface sprawl occurs in this scenario. This sprawl is further magnified by weak planning legislation, which leads to uncontrolled development.

The SSP trends explored for Europe tend to show similar directions of change to the countries within which the IMPRESSIONS regional/local case studies sit, i.e. Spain and Portugal (Iberia), Hungary, and the UK (representing trends for Scotland). Overall, the AS increase tends to be highest in the UK and Spain projections (i.e. always above the European average except for Spain in SSP3). Trends for Portugal tend to be closest to the European average. Hungary and Bulgaria have the lowest AS growth with increases in AS between 0% and 1%. The exceptions are: (i) a 13% AS increase in 2100 in the SSP3 scenario for Bulgaria, which is the only country reversing population decreases by 2100; and (ii) a 61% AS increase in 2100 in the SSP5 scenario for Hungary consistent with population growth, albeit at much slower pace than the UK, Spain and Portugal.

The broadscale European trends, as outlined above, follow the predicted socio-economic response (and storyline) of each SSP but show variability across countries. When mapped at the detailed model resolution (10' cells) increased spatial variability in the patterns of AS change become evident (Figure 16).

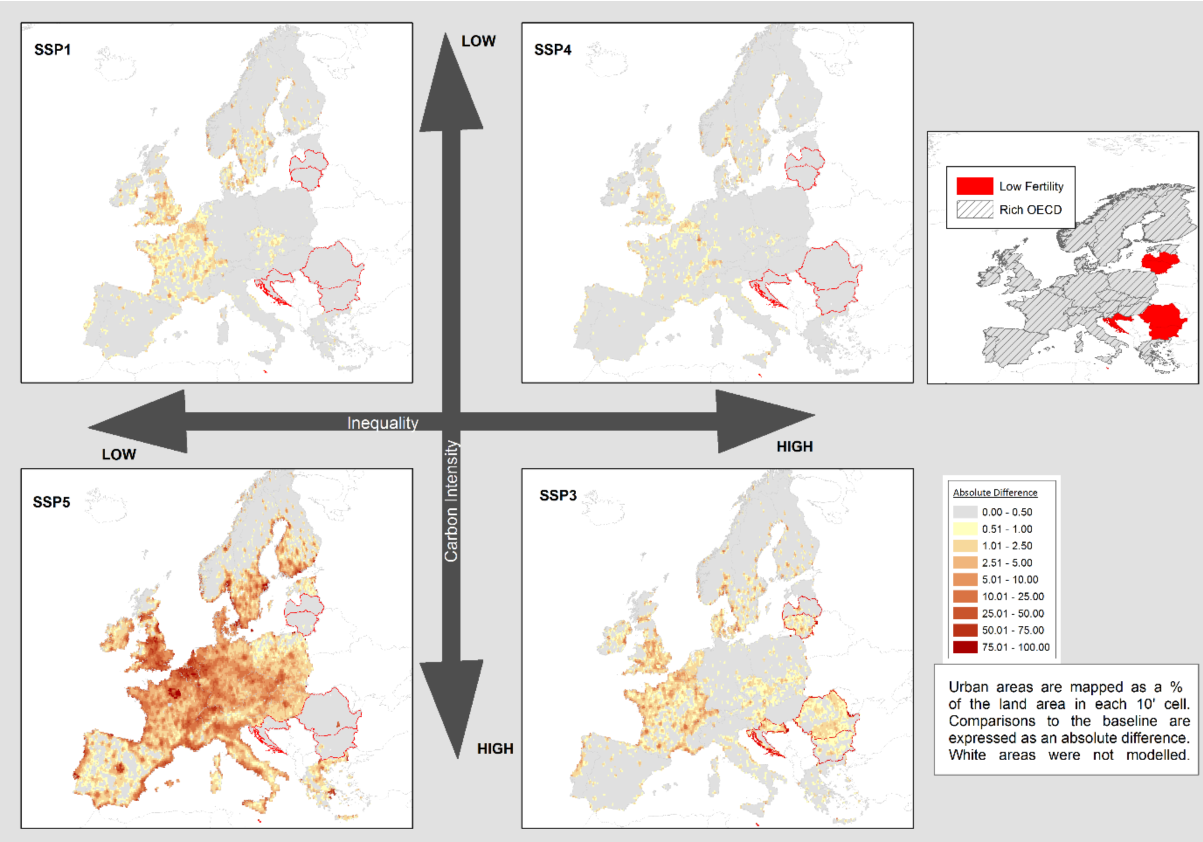


Figure 16: Map of the projected change, from baseline 2010, in artificial surface extent (as a percentage of the 10' cell land area) by 2100 under the four SSPs, highlighting trends for European low-fertility countries (outlined in red).

Population change estimates for low fertility countries in Europe do not predict the significant increases in population associated with SSP5 in the remainder of Europe. Instead, within SSP5, the countries are characterised by an aging but overall decreasing population. As a consequence of this declining population, model outcomes predict that the population could be housed within the existing artificial surface footprint (although the housing stock may change) limiting artificial surface expansion and urban sprawl (Terama et al., 2017). In contrast to the remainder of Europe, within the subset of countries, the highest artificial surface change (and urban sprawl) is associated with SSP3. While SSP3 is also characterised by an aging and declining overall population, the slower rate of change combined with a shift towards suburban development (associated with urban migration and weak planning laws) results in artificial surface expansion. In this context it is evident that a declining overall population is insufficient to prevent artificial surface expansion if changing demographics and/or residential preferences result in a shift to more expansive residential types. The rest of Europe more closely follows the broad trends with the most substantive artificial surface expansion occurring in SSP5.

The analyses suggest that spatial variability should be interpreted carefully to understand what assumptions are reflected in the results. In the case of the same SSP narrative, artificial surface trends reflect fertility assumptions developed at the global scale for each country (in low fertility countries, such as Bulgaria) and scenario assumptions on population growth (global and national scale) and aging (European and NUTS2 scale), especially when the two trends follow a similar growth path.

Assumptions on spatial development and population growth, within European-scale modelling, directly influence pan-European modelling outcomes. For this reason, we propose the integration of local SSP narratives in the assumptions, in particular the key trends of urbanisation and assumptions of population growth (with a special focus on migration) to analyse divergences and similarities at local (Iberian, Hungarian and Scottish) and European scales.

In SSP1, the global and European assumptions on urbanisation reflect a fast urbanisation process as a result of high income growth (Jiang and O'Neill, 2017). The European SSPs, however, further specify that the shift towards compact cities is tempered by a preference for green space. In the Iberian case study people move from cities to rural areas, preferring small towns to cities and contributing to the "repopulation of the countryside", suggesting that stakeholders did not consider living in small settings to be inconsistent with a sustainable lifestyle. A similar interpretation, but more directed at correcting current trends of depopulation of the countryside, has been provided by the Scottish and Hungarian stakeholders. More specifically, in Scotland, the countryside is the destination of incoming migrants to "reinvigorate communities" and, in Hungary, small towns become an attractive alternative to "overpopulated" Budapest. The migration trends are consistent across scales (global – European – local), with the exception of Scotland: the "medium" trend of the global SSP1 is the result of "low immigration and limited movements in Europe" and a balanced migration in Iberia (explicitly accounting for lower emigration). In Scotland, instead, returning emigrants and foreign migrants result in strong migration flows.

In SSP3, the global assumptions reflect a slow urbanisation process as a result of low income growth, limited mobility and poor urban planning (Jiang and O'Neill, 2017). This does not mean that cities will not grow in Europe: cities will grow at the fringes, because of sprawl, due to the lack of economic opportunity and consequent countryside abandonment. In the Iberian case, cities are assumed to grow as a result of low employment and countryside depopulation. In the Hungarian case study, low employment and poor urban planning result in the opposite trend (i.e. people's movement to the countryside and the urban fringe from larger cities). Migration is not a straightforward driver: globally, low migration is assumed; in Europe as a whole there will be emigration; whereas in the local case studies: high immigration from Africa and emigration from Iberia, low migration to and from Scotland, and high immigration is assumed for Hungary.

In SSP4 the global assumption is that income inequality between rural and urban regions acts as a pull factor towards urbanisation, although aging is assumed to be a limiting factor in the rural to urban mobility. Similarly, in the European SSP4 densely populated cities attract more and more dwellers resulting in the creation of urban ghettos. This trend is consistent with the Hungarian and Scottish case studies. In Scotland "the unemployed and new immigrants are forced to move to overcrowded housing surrounding the cities and main towns" and in Hungary there is a continuous movement from rural areas to cities. As in SSP3, migration trends vary greatly across regions in SSP4. In Iberia and Hungary a strong European Union is assumed to effectively control immigration, however, a wave of immigration affects Scotland throughout the scenario. Overall, the European narrative assumes controlled migration but introduced also the flows of illegal immigrants (which is not accounted for in the modelling exercise).

In SSP5 the global assumption is that mobility is high, which is also the case in the European SSP5. However, the global assumption of compact urban development is not consistent with the European SSP5, which is characterised by affluence-driven sprawl and strong preferences for pristine surroundings. In this scenario the demand for new artificial surfaces is by far the highest. In the case studies, within Iberia, movement to cities is strong following job opportunities in corporations. At later time points, some major cities such as Madrid are gradually abandoned as people migrate towards the coast. For the Scottish case study, most people are expected to be living in urban areas. In terms of migration, the scenario also depicts large numbers. This is in line with the overall population development which is one of the strongest growth. At the European level, migration is assumed to be mostly towards Europe from less strong economies. Also in the case studies, migration from Africa is expected to Iberia and the rest of Europe. Retired, rich northerners will also move to Iberia. By the end of the century, however, a collapse of the existing development model leads to emigration from Iberia towards northern Europe. Mobility is expected to be high for professionals across Europe.

By 2100, artificial surfaces within SSP5, still constitute less than 10% of the European land area. However, the magnitude and spatial distribution of this change has the potential to (i) increase the competition for land (for example, for food production or nature protection) with potential tensions between land use owners/interest groups, and (ii) detrimentally impact ecosystem services and biodiversity both within urban areas and in neighbouring regions. Impacts would affect not only the extent of natural areas but their quality given the market rather than ecological focus of society in this scenario (see also Güneralp and Seto, 2013).

The conclusion of the analysis is that scenario trends, developed at the European scale and combined with downscaled global trends, propagate assumptions on fertility trends made at the global to the regional scale into European scenarios at the NUTS2 scale. Results might be misinterpreted, if scenario users and other modellers are not aware of the full spectrum of uncertainties/assumptions and their accumulation/interaction across scales. This highlights the importance of understanding what assumptions are behind European scale trends and how they should be interpreted to be relevant to both European and local policy-making.

3.2.4. Integrating qualitative and quantitative socio-economic scenarios using Fuzzy Sets

The section (based on Pedde et al., 2018) describes the rationale and approach for integrating qualitative and quantitative scenarios in IMPRESSIONS to link the SSP narratives to the impact models in WP3 using the Story-and-Simulation approach (SAS) and Fuzzy Sets.

SAS consists of a ten-step approach aimed at developing and translating (often stakeholder-led) narratives into (often scientist-led) model quantifications, iterating and revising them until they are linked (van Vliet et al., 2010). SAS yields credible, plausible and innovative scenarios because of the inclusion of expert models combined with other creative elements introduced by stakeholders (Alcamo and Henrichs, 2008). The co-production also ensures consistency when it is necessary to go beyond what models can provide (Kemp-Benedict, 2012; Schweizer and Kriegler, 2012). The final scenarios are more relevant and legitimate for end-users as stakeholders can identify their views (i.e. stakes) in the storylines.

Although conceptually strong, operationalizing SAS reveals two issues: the ‘reproducibility’ and ‘conversion’ problems (Alcamo, 2008) as discussed in detail in Pedde et al. (2018). The problem of reproducibility exists because assumptions and mental models are not explicit when a scenario narrative is developed, whereas the conversion problem exists because narratives cannot be directly translated into quantifications. Scenario studies have tended to focus on addressing the ‘reproducibility’ problem (Voinov and Bousquet, 2010), so addressing the ‘conversion’ problem is urgently needed. However, tackling the reproducibility and conversion problems in SAS requires an understanding of the gaps in knowledge or uncertainties within both qualitative and quantitative scenarios separately, before combining them (van Vliet et al., 2010).

The main sources of uncertainties are epistemic, aleatory and linguistic (Uusitalo et al., 2015). Epistemic uncertainty is due to imperfect knowledge about something that is theoretically knowable. Aleatory uncertainty relates to unavoidable variation in stochastic processes. Statistical models represent uncertainty “in terms of (aleatory) probability distributions and (epistemic) parameters” (O'Hagan et al., 2006). Linguistic uncertainty is inherent to our natural language and includes vagueness and ambiguity (Regan et al., 2002). In SAS, the linguistic and epistemic sources of uncertainty remain separate until narratives are translated to produce quantifications. Therefore, narratives and models are treated as two separate products so that, although methods have been created to translate narratives into quantification, a clear methodological link between narratives and models is still lacking (Houet et al., 2016).

Currently, two main approaches address the SAS ‘conversion’ problem systematically and transparently: a Bayesian reasoning approach outlined by Kemp-Benedict (2010) and a Fuzzy Sets based approach as outlined by Kok et al. (2014) (based on Onigkeit et al., (2007). Kemp Benedict (2010) uses Bayesian statistics to propose a direct quantification of narratives in terms of how much they differ from a reference or historical dataset. The Bayesian statistics approach tackles the conversion problem by converting qualitative elements directly into the desired model input, without extra data processing. Notwithstanding that statistical approaches – both frequentist and Bayesian – structure uncertainty due to unavoidable randomness and imperfect knowledge, we argue that including this in participatory (stakeholder) scenario development poorly covers the full spectrum of uncertainty. Even a systematic and transparent approach such as Kemp Benedict`s (2010) is not universally applicable: assumptions are quantified in *a priori* distributions, and we question whether starting from such assumptions is realistic when historic data are scarce and/or ambiguous, and the participatory setting is characterized by diverging stakeholder expertise.

Alternatively, a Fuzzy Sets based approach accounts for linguistic uncertainty. This is important when narratives are developed by stakeholders in participatory settings and, hence, include vague or imprecisely-defined terms and elements within the narratives due to the heterogeneity of assumptions (e.g. from a wide range of viewpoints and expertise) (Mallampalli et al., 2016). This approach was therefore further explored for converting the qualitative stakeholder-derived narratives in the IMPRESSIONS socio-economic scenarios to the quantitative model inputs required by WP3.

The Fuzzy Sets approach was applied in the first set of stakeholder workshop held in each case study (see Deliverables D2.2 [Kok and Pedde, 2016], D6A.2 [Zellmer et al., 2016] and Pedde et al. (2018) for further details). Given inevitable time constraints and the importance of completing all steps within the workshop, the maximum number of variables that could be quantified by stakeholders was limited to three or four. These variables were selected based on two criteria. First, the variables had to reflect the expertise of most of the invited stakeholders, and nest well among the key issues for the case study. Second, the variables should relate to model input parameters that were among the most sensitive in the model. For the European case study, the results of a full sensitivity analysis of the main case study impact model, the IMPRESSIONS Integrated Assessment Platform 2 (IAP2) (Kebede et al., 2015) was available to support the choice of sensitive variables. In addition, stakeholders provided qualitative guidance to inform the quantification by the modellers of a much wider range of socio-economic variables used within all the case study impact models. For example, stakeholders provided trends for four capitals (human, social, manufactured and natural) of resource availability (Porritt, 2007) to be applied to model vulnerabilities to climate change (Dunford et al., 2015). Stakeholders were asked to estimate trends and quantification of variables, as well as provide an indication of their confidence when quantifying each variable.

The analysis of the range of stakeholder quantifications assumes that each stakeholder has a different, but equally valid, interpretation of the same statement due to different backgrounds, beliefs, knowledge, and so on. This means that each stakeholder could have a different interpretation of the linguistic term 'high increase' in a model variable, such as food imports compared to 2010. Each stakeholder, therefore, defined what they personally meant by 'high increase' by providing a numerical range.

Individual stakeholder ranges were represented with fuzzy numbers in a membership function (see, for example, Cornelissen et al., 2001). According to fuzzy logic, 'high increase' is a vague statement that should be addressed in a mathematical form (Zadeh, 1975a, b). If stakeholders can quantify such linguistic terms, their uncertainty would be neither epistemic nor aleatory but rather linguistic. We define the analysed variable a 'linguistic variable' with a 'linguistic value'. A linguistic value is the vague analogue of a numerical value and is the imprecise non-numerical value of a linguistic variable (Zadeh, 1975a). Linguistic variable and model variable have the same meaning to reduce the risk of misinterpretation.

A linguistic variable can have several linguistic values. In the example where the linguistic variable is 'Change in food imports from 2010', the variable has five linguistic values ranging from 'high decrease' to 'high increase' (Figure 17). The purpose of the linguistic values is to inform the calculation of fuzzy membership functions, based on the numerical range provided by each individual stakeholder of each linguistic variable, which will be used as model inputs.

The last step is the defuzzification of the linguistic value using one of various existing operators. The operator used here is the centre of gravity (CoG), a continuous defuzzification operator, which means that small variations in an input should result in small changes in output values (Leekwijck and Kerre, 1999). The centre of gravity of the membership function is defined in equation (1) by the minimum, median and maximum values of each linguistic value obtained from the results of the entire stakeholder group (Kok et al., 2014). The single value obtained with the CoG method is then applied to convert the qualitative changes into quantitative changes for each scenario. The quantified changes are then run in the WP3 impact models.

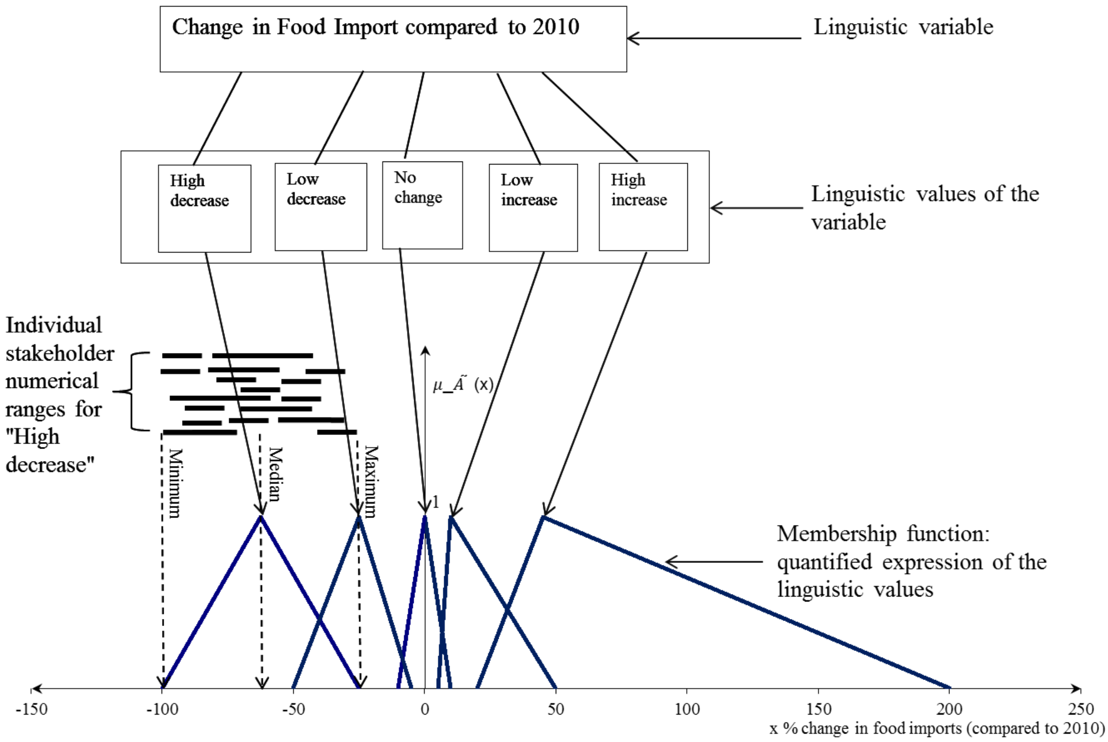


Figure 17: Representation of the linguistic variable 'Change in food imports compared to 2010) and its linguistic values, together with the numerical ranges provided by each stakeholder for a linguistic variable and the fuzzy restrictions. Membership functions define the degree of membership (μ_Ã in y-axis) of fuzzy numbers in a 0-1 scale (adapted from Zadeh, 1975a).

The quantification of the SSP narratives is used in all the WP3 impact models. Specifically, the IMPRESSIONS IAP2 used in the European case study uses the quantifications to derive probability density functions (PDFs) for each model input. For each linguistic value of each linguistic variable, the CoG represents the single output of a fuzzy set. We define the CoG as the default value of the membership function. The variation in values around this default value is taken to define the quantification uncertainty, which must be taken into account in subsequent analysis (modelling) steps. Generally, this can be achieved by representing the variation as a PDF, allowing the form and range of the stakeholders' quantification to be retained, and also allowing parameter sampling for rigorous sensitivity or uncertainty analyses. In the case of the IMPRESSIONS IAP2, input parameter values were assigned different (linguistic) ranges: a 'credible' range within which the 'default' value occurs and a wider 'possible' range. Assuming a probability distribution for the CoG, we define, for each linguistic variable, a 'default', a 'credible' and 'possible' range.

Beta-distributions are often chosen in the literature when non-normality is assumed due to their flexibility and limited ranges (Brown et al., 2014); however, they are not universally appropriate. Distributions are fitted to each linguistic variable CoG with an online tool[1] on the basis of a scaled default value and the 10% or 90% limits. These limits set the credible range for each scenario. Finally, we assign the scaled CoG value as 'default value', the 90% range for the 'credible range' and the 95% range for the 'possible range'. This choice is based on previously selected confidence ranges with the

[1] http://epitools.ausvet.com.au/content.php?page=BetaParams1. Tested by Brown et al. (2014)

IAP1 (Brown et al., 2014), but also on expert judgement on the distributions fitted to the data obtained by stakeholders.

As the CoG consists of the defuzzification of a single linguistic value, defuzzifying all linguistic values of a given linguistic variable is necessary to quantify the scenarios trends. These values are then applied according to the scenarios generated by stakeholders. The results suggest that the distribution fitted to the scaled CoG (interpreted as the mode of the distribution) is close to a uniform distribution. Based on an assumption of quasi-uniformity, the PDF ranges resulted in similar ranges to the membership functions for all quantified IAP2 variables. Thus, 90% of the PDF was close to a 0.1 degree of membership and the 95% of the PDF was close to a 0.05 degree of membership in the Fuzzy Set function (Figure 18). The quasi-uniform distributions suggest the possibility of fuzzy numbers to directly provide all IAP2 input ranges (default, credible and possible) and to account for nearly all ranges by stakeholders by staying very close to the minimum and maximum of the fuzzy number (up to 0.05 membership). From a conceptual perspective, the quasi-uniformity is also consistent with our assumption of allowing stakeholders to define the likelihood of their quantifications by providing a ‘range’ instead of a ‘most likely value’ of each linguistic value and a ‘confidence’ index; presumably this also suggests substantial uncertainty across stakeholders with wider ranges the more stakeholders are included.

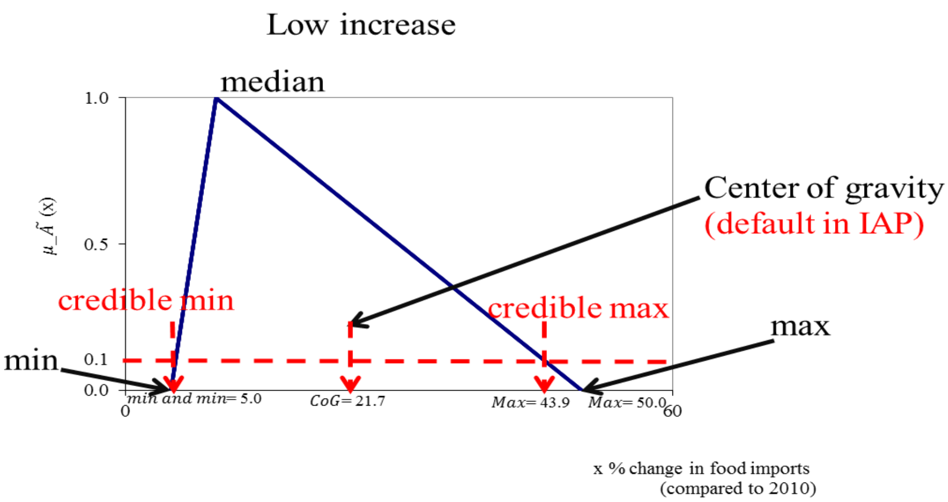


Figure 18: Visualisation of 'default’ and ‘credible range’ for the Integrated Assessment Platform 2 using stakeholder derived quantification.

This analysis is the first to show that stakeholders can provide reasonable quantitative ranges for model input variables based on the narratives they have developed. Even though a formal validation step may lead to changes in the method, the core steps described are transparent and can be reproduced in any workshop settings.

3.3. Societal tipping elements

The role and implications of societal tipping elements has been studied to a much more limited extent than climatic tipping points. At the same time, the transformative governance that will be needed for meeting the 1.5°C target of the Paris Agreement necessitates a shift in current governance systems and "proactive" societal change in order to develop transformative solutions to climate change.

Similar to the work described for climate scenarios in Section 2.6, non-linear changes in the socio-economic, political, institutional and cultural sub-systems within the SSP narratives were identified. For example, very rapid changes in human consumption (e.g. preferences for red meat), or economic development (e.g. rollercoaster development), were regarded to be candidates for societal tipping elements. The SSPs offer insights on non-linear changes of parts of the system, but not on the exact point in time when the change will take place, nor the exact magnitude of the change, nor the degree to which the change is irreversible. Yet, changes do indicate sudden, large-scale, non-linear dynamics that demonstrate that changes might be difficult to reverse and for which the system is potentially sensitive, hence the indication of potential tipping elements. Mathematical models would be needed to further explore dynamics and identify tipping points. Note that there is a rather large body of literature related to transitions, transformations and regime shifts, but usually to reach a new desirable system configuration. Hence, this is the first time that narratives of socio-economic change as developed by stakeholders have been analysed to identify tipping elements.

The analysis here focuses on the European SSPs, as they were tightly coupled with the global SSPs, while forming the context for SSP development in the other case studies. Narratives were analysed and all indications of non-linear change were identified. We looked for words indicating:

- Rapid change: "suddenly", "strongly", "rapid", etc.
- Strong change: "disintegration", "breakdown", etc.
- Novel system configurations: "new", "novel", etc.

The narratives of other case studies were also scanned for potential indications of tipping elements and compared with analysis for the European SSPs.

3.3.1. Tipping elements in the European SSPs

Table 5 shows potential tipping elements in the four European SSPs. The analysis reveals some observations:

- All SSPs have multiple tipping elements with an equal number of positive and negative aspects. These include a mix of rapid change ("rapid progress" in technology), strong change ("breakdown of the EU"), and novel system configurations ("new flexible institutions").
- Tipping elements relate to all forms of capital (human, social, financial, natural), except manufactured.
- The most positive (SSP1) and the most negative (SSP3) scenario have the most positive and negative tipping elements, respectively. The parts of the narratives describing later time periods (i.e. futures rather far from today's reality) are in need of multiple tipping points to tell a plausible story. In SSP1 the focus is on positive tipping elements towards a new system based on low material growth and with a focus on well-being; in SSP3 the focus is on the breakdown of society.

- Multiple positive tipping elements are found in the energy sector (SSP1 and SSP4); whereas technological progress is strong in many scenarios, but only identified as a tipping element in SSP5. Institutions and human capital are only identified as positive tipping elements.
- Multiple negative tipping elements are found in societal changes (SSP3 and SSP4), and environmental degradation (SSP3 and SSP5).

Table 5: Socio-economic potential tipping elements in the European SSPs.

Tipping elements	SSP1	SSP3	SSP4	SSP5
Energy	+ Sector to renewables		+ Towards high-tech green Europe	
Technology				+ Rapid progress in all sectors
Social capital		- Disintegration of social fabric	- Low and stratified social cohesion - Quickly dwindling middle class and rising inequalities	
Political system	+ Focus on well-being rather than economic growth	- Political instability - Breakdown of the EU		
Institutions	+ New flexible, multi-scale institutions			
Civic society	+ Consumption to low material growth	- People learn to live with less		
Human capital				+ Rapid improvement of education and health care
Ecosystems		- Severe ecosystem failures		- Serious environmental degradation

The European SSP scenarios include a range of positive tipping elements, importantly related to changes in the energy sector, and the role of (new) institutions and political stability, also supported by rapid technological change. The scenarios also include a range of negative tipping elements, importantly related to environmental degradation and collapse of (current) institutions. The socio-economic scenarios, therefore, increase the need for transformative solutions that reverse environmental degradation, sometimes in combination with the degradation of social fabric and/or breakdown of the EU.

3.3.2. Cross-scale analysis of societal tipping elements

The narratives of the Scottish SSPs generally emphasise gradual change, by the repeated use of phrases such as “slowly phased out”, “slowly adopting”, “steady economic growth”, or “does not happen overnight”. None of the narratives provides indications for strong or rapid change. Yet, the final situation in Scotland is often fundamentally different than the starting point. Similar to the

European SSPs, society breaks down (SSP3), a new economy emerges (SSP1), and environmental degradation "reaches a tipping point" (SSP5). This suggests that there are potential tipping elements.

The narratives in Iberia, on the other hand, very frequently use a large number of phrases that indicate rapid, non-linear change: "destructive impacts"; "a series of dramatic events"; "strong and enduring"; "record levels"; "increasingly strong". All narratives also provide indications of systemic change, again similar to those in the European SSPs.

The narratives in Hungary, finally, are similar to the Scottish SSPs with a strong focus on systemic change, but without emphasising strong or rapid changes, but there are frequent use of words such as: "new generation"; "destabilise the country"; "a completely different culture evolves".

According to the stakeholders, the potential emergence of new systems' configurations or positive tipping points will be dependent on the development of transformative capacities of agents in the following systems:

- **Energy systems:** full switch to renewable energies and a move towards an energy self-sufficient Europe in a way that makes full use of its context-dependent potential (e.g. solar energy in southern Europe).
- **Governance:** civic participation if fully developed, with fair multi-level coordination and international cooperation in line with a shared, integrated and long-term sustainability orientation.
- **Socio-cultural:** European society widely adopts and normalises sustainability behaviours and is engaged in continuous learning and reflexivity.
- **Technological systems:** Green high-tech and low-tech infrastructure systems are fully integrated in Europe (e.g. household rainwater collection, integrated water sensitive infrastructure, green biodiversity corridors).
- **Resource systems:** full move towards a circular economy and towards organic agriculture.
- **Economy:** integrating ecosystem services, and a focus on quality of life and social wellbeing is integrated into the core economic activity.

In conclusion, narratives in all case studies indicate that there will be systemic changes that will lead to radically different socio-economic futures, in terms of civic society, (multi-level) governance, and/or technological progress. Yet, in some case studies the gradual nature of the dynamics is emphasised (Scotland), while in others changes are described as strong and/or sudden. To what extent the use of words represents the nature of the language and the meaning of words and the common practice of communications, and to what extent it represents differences in the actual changes, needs to be further investigated. Nevertheless, the differences in trends of sudden changes, as stated by Spanish and Portuguese stakeholders, to gradual transformations, as stated by Scottish stakeholders, seems to match other cultural differences.

4. Integration and synthesis of the climate and socio-economic scenarios

4.1. Definitions, and conceptual and practical considerations

"Integration" is a word that is very often used, particularly in the climate change community. Any climate change impact, adaptation/mitigation option, or pathway can only be meaningfully discussed against the backdrop of an "integrated scenario" that combines climate and socio-economic scenarios. However, it is not often made explicit how information is integrated. Typically, and stimulated by the new set of global scenarios where socio-economic (SSP) and climate (RCP) scenarios are separated, integration takes place when applying (integrated assessment) models. Although this is a valid method to integrate, integration is broader, which also calls for a conceptual understanding of what is integrated and by whom.

Here we define integration as the process of bringing together climate and socio-economic information on future outlooks that is subsequently used to produce new information in which both sources of scenarios are considered. This can include model input, model output, pathways, altered scenarios, etc.

In this section, three ways in which scenarios were integrated are reported. First, we tried to integrate climate change effects in the socio-economic scenarios by having stakeholders alter the narratives. Second, and most importantly, we have applied multiple models where climate and socio-economic information was brought together to project climate change impacts. Third, we have used climate and socio-economic scenarios to contextualise adaptation and mitigation pathways, resulting in RCPxSSP-specific, integrated pathways (see Figure 19).

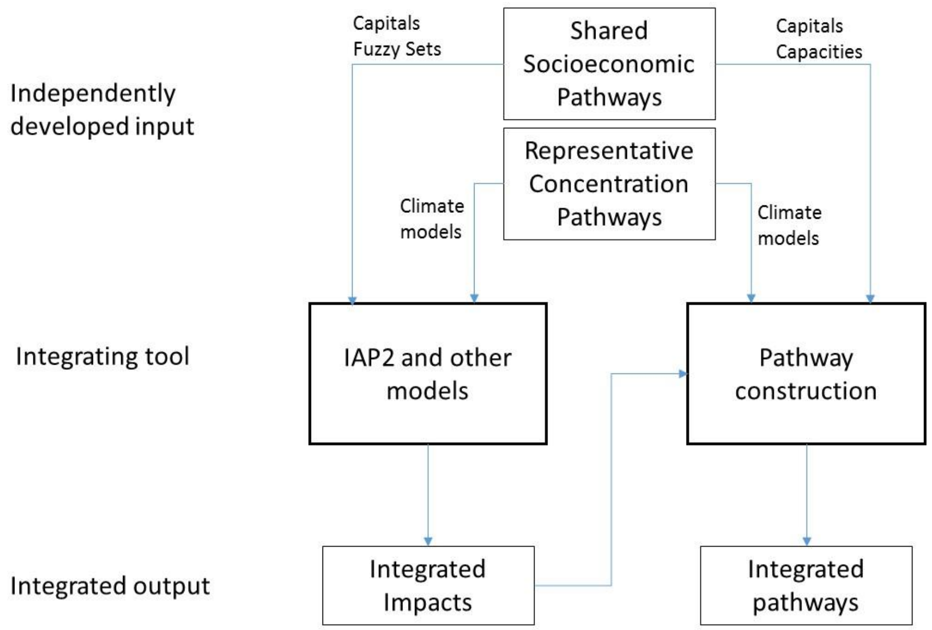


Figure 19: Schematic illustrating different ways of integrating climate and socio-economic scenarios.

4.1.1. Selection of RCP × SSP combinations

In order to limit the number of combinations between RCPs and SSPs, and hence to limit the practical implementation of integrated climate and socio-economic scenarios, we selected five RCP×SSP combinations early in the project, in line with global discussions on 'most probable' emissions from any socio-economic scenario (see Table 6). In addition, later in the project following a request from the European Commission, scenarios based on RCP2.6 were added to address implications related to the Paris Agreement.

Table 6: Selected RCP x SSP combinations and their characteristics.

	Low adaptation challenges	High adaptation challenges
High mitigation challenges	RCP8.5 × SSP5	RCP8.5 × SSP3
Low mitigation challenges	RCP4.5 × SSP1	RCP4.5 × SSP4 RCP4.5 × SSP3

In Section 4.2, integration is based on four RCP×SSP combinations (RCP4.5×SSP3 was excluded), to focus on the most probable combinations of RCPs and SSPs. In Section 4.3, integration is based on combinations of RCP2.6 and RCP8.5 with SSPs 1 and 3, to analyse two very different climate and socio-economic futures.

4.1.2. Spatial scale: Cross-scale integration

The process as depicted in Figure 19 was executed in all case studies, using scale-specific RCPs, SSPs, and models, building on the same set of RCPs, SSPs, and RCP×SSP combinations. This allows the different spatial scales of the integrated scenarios and their integrated products, i.e. model outputs and pathways, to be compared.

4.1.3. Temporal scale: Short-term versus long-term importance

Climate change is a slow process, where the strongest impacts of temperature and precipitation change are apparent only when looking at long-term future outlooks. This was one of the major considerations when selected the time horizon of 2100 for all scenarios developed in all case studies. Socio-economic changes can likewise relate to slow processes such as behavioural or institutional change. Yet, many of the socio-economic changes represented in the SSP scenarios are assumed to occur rapidly and thus become visible over shorter time horizons. This can make the climate signal less visible, compared to the socio-economic signal, particularly for impacts of RCP2.6 or RCP4.5.

Table 7: Assumed dominance of changes in observed integrated impacts.

	2040	**2070**	**2100**
RCP4.5xSSP1	SSP dominant	Both RCP and SSP	SSP dominant
RCP8.5xSSP3	SSP dominant	Both RCP and SSP	Both RCP and SSP
RCP4.5xSSP4	SSP dominant	SSP dominant	Both RCP and SSP
RCP8.5xSSP5	SSP dominant	Both RCP and SSP	RCP dominant

4.2. Integration through modelling

As pointed out in Section 4.1, the most important manner to integrate scenarios in IMPRESSIONS was through the use of (integrated) models. Here we present results related to the IMPRESSIONS Integrated Assessment Platform 2 (IAP2) to integrate climate and socio-economic scenarios.

4.2.1. Integration using the Integrated Assessment Platform 2 (IAP2) for Europe

The Integrated Assessment Platform (IAP) was designed to integrate climate and socio-economic scenarios and their impacts across multiple sectors. The second version of the IAP (IAP2) developed in the IMPRESSIONS project was adapted to include the RCPs and SSPs and to run until 2100. For a thorough analysis of the behaviour of the IAP2 model for a large number of model runs, we refer to Harrison et al. (2018). Here we build on the set of 91 IAP2 runs that were analysed and described for that paper. Specifically, we selected a subset that allows analysis of the effect of climate change, socio-economic change, and their combined impact. Table 8 show the characteristics of the selected IAP2 runs. Six runs were selected, including one with ‘low climate change’ based on RCP2.6 and current baseline socio-economics; one with ‘high climate change’ based on RCP8.5 and baseline socio-economics; two with ‘maximum and diverse socio-economic change’ related to SSP1 and SSP3 combined with low climate change (RCP2.6), and two with ‘maximum and diverse socio-economic change’ related to SSP1 and SSP3 combined with high climate change (RCP8.5). These six runs allow the effect of climate and socio-economic change to be quantified separately and combined, but also to calculate the added effect without combining impacts in a single run. Thus we can also assess the difference between integrating climate and socio-economic change and simply summing the impacts.

Because the analysis is mostly for illustrative purposes, a small set of three indicators, representing different sectors, were selected, focusing on those that are influenced by both socio-economic and climatic change. These include: the Water Exploitation Index (WEI), which is based on the ratio of water demand to water supply; carbon stock, which is based on the potential above-ground tree biomass; and the area of extensive grassland, which is used for sheep and rough grazing.

Table 8: Scenario settings for the selected IAP2 runs.

Description	Run #	RCP	SSP	Climate model	Time slice
Low climate change	9	2.6	Baseline	MPI-ESM-LR_REMO	2080s
High climate change	18	8.5	Baseline	CanESM2_CanRCM4	2080s
SSP1; Low climate change	26	2.6	SSP1	EC-EARTH_RCA4	2080s
SSP3; Low climate change	35	2.6	SSP3	EC-EARTH_RCA4	2080s
SSP1; High climate change	63	8.5	SSP1	CanESM2_CanRCM4	2080s
SSP3; High climate change	72	8.5	SSP3	CanESM2_CanRCM4	2080s

Overall, climate change increases the potential carbon stock (1.95 Mt; see Table 9), while socio-economic change reduces it by a similar amount (1.65 Mt), although there are large regional differences. Integrating runs show a positive balance for both SSPs. A number of specific points stand out:

- Overall, summing the separate effects of climate and socio-economic change results in much smaller increases of potential carbon stock, than when integrating changes in a single run. Where the effects of climate (run #18) and socio-economic change (#26 and #35) almost cancel each other out, integrated runs show a positive change in most regions, particularly for SSP3 (#72).
- For SSP3, the climate signal dominates in all regions and for the EU with very similar numbers for the climate run (RCP8.5 only) and the combined RCP8.5×SSP3 run.

Table 9: Total potential carbon stock (tonnes) for six IAP2 runs, for five regions and the entire EU. Between brackets change in carbon stock compared to run CARB9. Numbers refer to runs as indicated in Table 8.

Region	CARB9	CARB18	CARB26	CARB35	CARB63	CARB72	CARB 18+26	CARB 18+35
Alpine	575401	1002352 (426951)	510592 (-64809)	599027 (23626)	790847 (215446)	1024775 (449374)	(362142)	(450577)
Northern	1740205	2198289 (458084)	941964 (-798241)	1550335 (-189870)	1784362 (44157)	2191216 (451011)	(-340157)	(268214)
Atlantic	1486691	1656273 (169582)	1013461 (-473230)	469200 (-1017491)	1564240 (77549)	1609700 (123009)	(-303648)	(-847909)
Continental	725770	1743279 (1017509)	474646 (-251124)	575595 (-150175)	1316358 (590588)	1357957 (632187)	(766385)	(867334)
Southern	503982	380149 (-123833)	444641 (-59341)	183157 (-320825)	429402 (-74580)	330618 (-173364)	(-183174)	(-444658)
EU	5032048	6980341 (1948293)	3385304 (-1646744)	3377314 (-1654734)	5885210 (853162)	6514266 (1482218)	(301549)	(293559)

All runs in almost all regions show an increase of WEI (see Table 10). In general, the effect of climate change is much lower (0.02 increase across Europe) than the effect of socio-economic change (0.19 increase). For separate regions in Europe, this effect is even more pronounced, particularly in water-limited southern Europe. When combining socio-economic and climatic change, WEI mostly increases more strongly indicating greater water stress. A number of specific points stand out:

- Overall, summing the separate effects of climate and socio-economic change results in larger increases of WEI, than when integrating changes in a single run. For SSP1, for example, integrated change results in a WEI increase of 0.17, while adding results of separate runs results in an increase of 0.21. This holds for both SSPs and for most regions.
- In some cases, the integration of two positive impacts, results in a lower overall increase. For example, for SSP1, the increase due to socio-economic change (0.19; run #26) is *lower* than the increase when integrating with climate (0.17; run #63), even though the effect of climate change is also a small increase in WEI (0.02; run #18). This holds for a number of regions and for both SSP1 and SSP3.

- For the region Continental, the integrated runs produce almost exactly the same results as the separately added effects.
- For the region Southern, the additional effect of climate change is much larger for SSP3 (from 0.39 to 0.53) than for SSP1 (from 0.44 to 0.48), with a higher WEI in SSP3 than in SSP1, despite a larger socio-economic change. This reflects the nature of the socio-economic change with more water savings through behavioural and technological change in SSP1 compared to SSP3 which reduces the impacts of climate change on water stress.

Table 10: Water Exploitation Index (WEI) for six IAP2 runs, for five regions and the entire EU. Between brackets change in WEI compared to run WEI9. Numbers refer to runs as indicated in Table 8.

Region	WEI9	WEI18	WEI26	WEI35	WEI63	WEI72	WEI 18+26	WEI 18+35
Alpine	0.054	0.061 (0.0005)	0.146 (0.10)	0.139 (0.09)	0.132 (0.08)	0.124 (0.07)	(0.10)	(0.09)
Northern	0.025	0.021 (-0.0005)	0.045 (0.02)	0.043 (0.02)	0.084 (0.06)	0.082 (0.06)	(0.02)	(0.01)
Atlantic	0.118	0.136 (0.02)	0.195 (0.08)	0.247 (0.13)	0.174 (0.05)	0.301 (0.18)	(0.01)	(0.15)
Continental	0.217	0.233 (0.01)	0.596 (0.38)	0.545 (0.33)	0.608 (0.39)	0.571 (0.35)	(0.39)	(0.34)
Southern	0.215	0.410 (0.18)	0.660 (0.44)	0.608 (0.39)	0.695 (0.48)	0.753 (0.53)	(0.62)	(0.57)
EU	0.121	0.141 (0.02)	0.311 (0.19)	0.305 (0.19)	0.290 (0.17)	0.318 (0.20)	(0.21)	(0.21)

Results for extensive grassland are shown in Table 11. Overall, the effect of climate change is enormous with the almost total disappearance of extensive grassland across Europe. The effects of socio-economic change are less strong, but with a similar trend towards less extensive grassland. The combined effect is that the area of extensive grassland completely disappears in the integrated runs. Some specific observations:

- Overall, summing the separate effects of climate and socio-economic change results in larger decreases of the area of extensive grassland. Note, however, that this simple method results in a decrease of area of more than 100%, which is not possible.
- The climate signal dominates for both SSPs, as extensive grassland completely disappears.
- Both signals are strong and in the same direction, which makes it difficult to disentangle the separate influences.

Table 11: Area of extensive grassland for six IAP2 runs, for five regions and the entire EU. Numbers refer to runs as indicated in Table 8.

Region	EXTG9	EXTG18	EXTG26	EXTG35	EXTG63	EXTG72	EXTG 18+26	EXTG 18+35
Alpine	4730598	0	4644636	3672363	0	0		
Northern	4837420	0	12149048	1084649	0	0		
Atlantic	12083419	913627	5412350	10074362	0	0		
Continental	10300081	0	4212339	6003068	0	0		
Southern	15146075	110671	7696977	7776273	0	0		
EU	47097594	1024298 (-46073296)	34115350 (-12982244)	28610715 (-18486879)	0 (-47097594)	0 (-47097594)	(-59055540)	(-64560175)

A number of conclusions can be drawn based on the IAP2 model runs that were analysed. Importantly, we do not claim that these conclusions have any validity beyond the set that was examined. A more extensive analysis across more RCPs, climate models, SSPs, and/or sectoral output indicators would be needed to extend conclusion beyond the small set included here. Yet, as they cover a set of representative input scenarios and output indicators, they can be used as indications.

- **Models capture the complexity of the system beyond a "simple" addition of separate input parameters, and are therefore the preferred method of integration**. Summing the climate and socio-economic signal almost always provides a different estimate than when analysing an integrated model run. There is no consistent trend across the three indicators: the summed impact is sometimes larger (WEI), sometimes smaller (carbon stock), and sometimes results in unrealistic estimates (grassland). Clearly, the integrated model runs account for climate and socio-economic change beyond the simple summing of the separate effects. The application of integrated climate and socio-economic scenarios are therefore the best way to make use of an integrated model such as the IAP2.
- **Model integration results in outcomes that cannot be explained from the separate inputs.** In some cases and particularly when both signals are strong and in the same direction, there are "contradictory" results. The dampening of a positive, socio-economic induced change by an additional also positive climate change signal, for example, is counterintuitive. Most likely, there is a complex mix of cross-sectoral effects that influence the outcome of multiple rather than single drivers.
- **Models strongly account for the climate signal, possibly related to the strong representation of biophysical parameters for extensive grassland and carbon stock.** In this limited comparison, the climate signal dominates in land related indicators, both when it is very strong (extensive grassland) and when its signal differs in direction from socio-economic signal (carbon stock). This is in disagreement with the analysis of a broader set of indicators in Harrison et al. (2018), where the SSP signal by far outweighs the climate signal.

4.3. Integration by adjusting SSPs

During the first series of stakeholder workshops, a specific session towards the end of the workshop was dedicated to the integration of climate and socio-economic change. After completion of the SSPs, stakeholders were asked to revisit their scenario to assess the impact of climate change on socio-economic change. Specifically, they were asked to change the narrative as a reaction to projected climate change. Stakeholders were presented with the RCP that was linked to their scenario (either

RCP4.5 or RCP8.5) together with a general description of global and/or European climate change in terms of precipitation and temperature with some indication of the occurrence of extreme events. A short overview of the results of this exercise for the SSPs in Central Asia is provided as an example, with a discussion of some more general issues and conclusions.

After completion of the first draft of the Central Asian SSPs, a presentation was given to introduce climate change and climate impacts in Central Asia. Stakeholders were provided with information on temperature change (average, summer/winter) and precipitation (average, seasonal), but importantly also on climate change impacts (food security, water availability, migration, river flows/flooding, drought, etc.). Impacts were summarised as:

- Climate change will have an impact;
- There will be major changes for all major water systems (wetter in the north, drier in the south);
- Glaciers will melt;
- Food security will be affected.

In four groups, stakeholders then discussed the impact of these changes on their storyline, with the following main changes being made to the SSPs:

In SSP1, climate change impacts would occur before 2050. These would then lead to an increased urgency to institutionalise measures and enforce policies much earlier. In SSP5, there would be serious consequences of climate change as this future has high challenges to adaptation. Again, most of the changes happening around 2050 – and particularly investments in water technology – would happen much earlier due to climate change (impacts). In essence in SSP3, climate change impacts would significantly worsen the outlook of many sectors and factors, including health, geopolitical stability, and water. Induced socio-economic change and ability to adapt were not discussed in great depth but are likely to be rather small as societies are vulnerable. The impact of climate change on SSP4 was considered to be relatively small, as this is a scenario with less climate change and a green elite that can act quickly and mitigate successfully.

Several observations emerge from this exercise in all five case studies:

- Extreme events act as catalysts, facilitating/accelerating both negative and positive developments. For example, migration and poverty in SSP3 worsen, while the transition to renewables happens earlier in SSP1.
- Long-term gradual change has little effect on the socio-economic stories.
- SSP5 stands out as a scenario where climate change and environmental degradation receives little attention in the basic story, and where institutional change is triggered that would otherwise not be in place due to climate change.

In summary, introducing climate change impacts in the SSPs led to changes in the SSPs. The most significant alterations are as a result of extreme weather events (droughts and flooding), happen before or around 2050, regard climate change as a catalyst of socio-economic change, and relate to the aspect of the SSP where challenges are low: mitigation in SSP4, adaptation and later mitigation in SSP5, adaptation and mitigation in SSP1, and impacts only in SSP3. Overall, the underlying logic of the stories was maintained, but the speed of change increased. It can thus be concluded that integrating SSPs and RCPs through stories leads to an integrated product which emphasises additional and more rapid institutional and organisational change that lower challenges to mitigate and/or adapt to climate change impacts.

Advantages of this method of integrating climate and socio-economic change are that the stakeholders themselves undertook the integration. Also, it served the purpose of bringing together RCPs and SSPs at an early stage of the project. The largest disadvantage related to the fact that the output of the session were sets of stories that included the effects of climate change. These were not useful as inputs to the various models that also include the integration between the two. The risk of double counting changes and their impacts led to use of the unaltered SSPs as inputs to the models in WP3, discontinuing the use of this integrated set of stories.

4.4. Integration through pathway construction: SSP×RCP×SPA framework in IMPRESSIONS

The new set of scenarios as put forward by the global climate change community have a third element in addition to the RCPs and SSPs; i.e. the Shared climate Policy Assumptions (SPAs; Kriegler et al., 2014). These are normative scenarios that provide additional information on mitigation and adaptation options. Integrated scenarios (i.e. combinations of SSPs and RCPs, integrated through integrated assessment models) are used as the starting point to explore the effect of climate policies. In IMPRESSIONS we used the same overall methodology of first developing integrated scenarios (WP2), that were used as input of a variety of models (WP3), that could then be used as starting point for pathways construction, yielding integrated pathways of adaptation and mitigation actions. In practice, however, the integration of RCPs and SSPs was only in part due to the sub-global scale of the IMPRESSIONS case studies: the global SPAs focus on mitigation scenarios, which use information from SSPs and RCPs, whilst the IMPRESSIONS pathways focus on adaptation, mitigation and transformative actions within the scales of the case studies (D4.2). Because the adaptive and transformative actions are not directly linked to mitigation through modelling, the feedback to climate change cannot be represented.

In the IMPRESSIONS process of developing scenarios and pathways (see Figure 20), the link between SSPs and RCPs was combined in two steps. The first step was during the first stakeholder workshop. The stakeholders developed local versions of the global SSPs with consideration of socio-economic drivers only and independently from the climate signal. At the end of the first stakeholder workshop, after the local SSPs were developed, the stakeholders discussed the implications for the socio-economic drivers once they had been shown future trends of temperature and precipitation based on the subset of climate models for RCP4.5 or RCP8.5. The second step was during the second stakeholder workshop. The stakeholders were shown both SSPs and RCPs together with integrated climate and socio-economic impacts for each scenario. All these elements, form the context scenarios, i.e. “what could happen” independently of the actions needed to achieve specific policy objectives (such as those of the vision). This step is part of the social-science based-inductive methodology developed in WP4, where pathways are fully normative and therefore the stakeholders fully determine how the scenario context can be utilised without pre-determined information or a “framework” to predetermine the action. Because of this reason, it is difficult to systematically analyse if SSPs, RCPs or integrated socio-economic and climate impacts influenced pathway development.

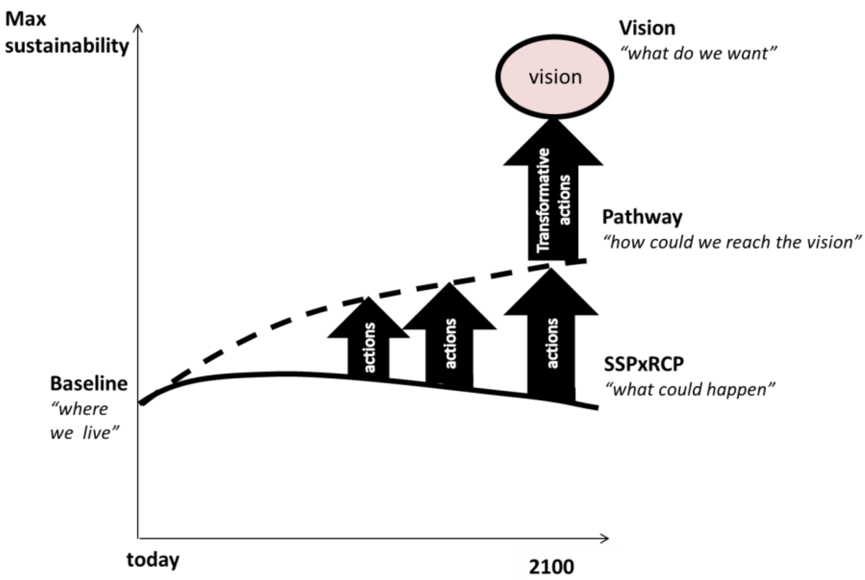


Figure 20: Conceptualisation of scenarios (SSP×RCP), pathways and visions in IMPRESSIONS.

4.5. Integration of tipping elements

For both climate and socio-economic scenarios, identification of tipping elements is indirect and can be analysed *ex post*, in impacts (for climate) and pathways (for socio-economics). The discussion of tipping elements in IMPRESSIONS is complicated by the scale of impacts, as analysed in the local case studies. While global scale theoretical tipping elements can be identified *a priori*, it is not straightforward to assess local tipping elements. Climate tipping elements are traditionally defined as large scale events, but it seems possible that local scale tipping elements may add up to have global effects and that multiple interacting tipping elements could have rather unknown implications - this could be the combination of extended droughts and a very strong heat wave or it could be the mutual interaction between abrupt societal and climate changes. Consistent with the bottom-up perspective of identifying patterns in local case studies, societal tipping elements have been identified from the SSP narratives, which point at strong and rapid change in the narrative.

Overall, the RCP×SSP architecture has enabled the analysis of climate and socio-economic scenarios for impacts, vulnerabilities and solutions. However, because in reality "socio-economic potential" and solutions are not separate, the choice of maintaining the artificial division between RCPxSSP and the impacts, vulnerabilities and solutions has resulted in an oversimplification of the role of the very complex interactions between agency and structure, and excluded the room for agency to act on structural thresholds (Olsson et al., 2015). In the SSP design, in particular, agency is implicit and feedbacks from effective solutions are not integrated in the narratives but are part of the pathways, because the socio-economic narratives are designed to portray the potential for mitigation and adaptation (O'Neill et al., 2017). For these reasons, a meaningful discussion of tipping elements in socio-economic scenarios should involve the feedback between the actions and strategies developed in pathways in the context of the SSPs. The SSPs developed in IMPRESSIONS offer ways to think about transformations in various systems including energy, governance, socio-cultural, technological and economic systems. In this way, we have explored which structural conditions and capacities in the SSPs could lead to positive fundamental systemic changes according to a normative vision of the future (see Deliverables D4.2 [Hölscher et al., 2017] and D5.3 [Carlsen et al., 2017]).

Having said that, the subsequent section offers some preliminary RCP×SSP-specific potential interactions between climatic and socio-economic tipping elements, indicating reinforcing or dampening potential.

4.6. Synthesis

In this section we synthesise all the different ways in which climate and socio-economic scenarios have been developed and combined, taking the European SSPs as the main entry point. This synthesis takes the form of short stories that sketch the future in terms of socio-economic change, climate change, and their integration, seen through multiple different methodological lenses. The pieces of text are meant to illustrate the differences between methodological viewpoints, the complementarities between them, and the need for a mixed methods approach to develop and quantify scenarios.

4.6.1. RCP4.5 × SSP1

The SSP1 story reports a high commitment to achieve sustainable development goals through effective governments and global cooperation, ultimately resulting in less inequality and less resource intensive lifestyles. The interplay of financial, environmental and economic crises fuel the feeling that behaviour has to change away from an unregulated market-driven economy to a sustainable development path. This puts governments under pressure to take ambitious measures, including stimulating an energy transition towards renewables and facilitating innovative research, accompanied by investments in health, education and social support. A decrease in conflicts in Europe's southern and eastern border regions leads to higher political stability and moderate but steady economic growth in an increasingly equitable Europe. The European Union expands further and participates in new global governance initiatives. Advances in green technologies are further stimulated by international competition leading to a CO_2 neutral society by 2050. By 2100, Europe is characterised by a high level of sustainability-oriented political and societal awareness, focusing on renewable energy and low material growth in a strongly regulated but effective multi-level governance structure.

The core set of climate models related to RCP4.5 project low to intermediate change until 2100, depending on the selected climate model. This nevertheless translates into considerable changes in average annual temperature of 2.5-3.5^{o}C, with in general higher values for Scandinavia and lower values for the UK, and with minimum values of 0.7^{o}C and maximum values up to 6^{o}C. Average annual precipitation values likewise change considerably towards 2100. With more spread between the different climate models, mean annual precipitation is projected to increase strongly in Scandinavia (up to +30-35%); moderately in mainland Europe (+5-15%); and decrease in the Mediterranean (up to -25%). Overall, climate change poses considerable challenges.

Impact model runs with the IAP2 illustrate how this climate change results in moderate changes in key indicators such as potential carbon stocks and the area of extensive grassland. In general, changes induced by socio-economic change are larger than by climate change, although the climate change signal on key indicators is relatively strong. Model runs furthermore show large spatial variability in climate change impacts in RCP4.5 × SSP1.

When stakeholders adjusted SSP1 based on the RCP4.5 climate change scenario, extreme weather events act as catalysts, accelerating positive developments, for example, with the transition to renewables happening earlier. This is caused by the low challenges to mitigation and adaptation in the socio-economic outlook.

SSP1 is furthermore characterised by multiple tipping elements that happen at various moments in time. These are mostly socio-economic (behavioural change; shift in energy sector) but might also include climatic tipping elements (melting of Greenland ice sheet and Alpine glaciers). Climatic tipping elements would pose additional adaptation challenges that are likely to be manageable in an SSP1 type of future.

SSP1 is a very consistent scenario across the case studies, with similar combinations of egalitarian and hierarchist worldviews, and very similar logic in the stories in all case studies. The egalitarian component is dominant, with equity and societal development as widely shared values. Nature is generally perceived as vulnerable and society tends to have a proactive attitude. The hierarchic component is most visible in the European and Scottish scenarios corresponding to a shared belief that a degree of top-down regulation is necessary.

When looking at capacities of actors across scales, the quick transition towards sustainability in SSP1 requires the maintenance and further improvement of capacities until 2100. Societal and environmental awareness is generated early in the scenario, resulting in high orchestrating, transformative and stewarding capacity that facilitates all major actor groups to act easily. Therefore, SSP1 in all case studies gets close to, but does not quite reach, the vision without the need for additional action.

In short, an integrated RCP4.5 × SSP1 future outlook is one of a path towards sustainability through strong governance, technology and behavioural change, sped up by extreme climate events early in the scenario, and facilitated by high levels of capitals and actor capacities. The outlook is consistent across scales and would require similar actions at any scale. Quantitative analyses and model explorations, however, stress the importance of climate change impacts across all sectors, possible worsened by climatic tipping elements. Although relatively low, RCP4.5-related climate change impacts are significant and need to be addressed to reach the sustainable vision.

4.6.2. RCP8.5 × SSP3

The SSP3 story explains how, sparked by economic woes in major economies and regional conflict, antagonism between and within regional bloc's increases, resulting in the disintegration of social fabric and many countries struggling to maintain living standards. With the economy gradually picking up, the demand for resources increases, which turns out to be a tipping point for the state of the environment with severe ecosystem failures. The persistence of conflicts and decline in trade also substantially increases energy and food prices, while initiating a massive build-up of the defence sector, which is resource hungry but not resource efficient. Long-term policy planning becomes rare with hardly any money for education, research or innovation. Eventually the EU breaks down, with new regional blocs forming in the north and south of Europe, while new alliances with other countries are forged to ensure sufficient energy supply. Social counter-movements temporarily appear but do not take root in a fragmented and divided Europe with strong regional rivalry and conflict. Ultimately, a high-carbon intensive Europe emerges that is not worse off than the rest of the world, but struggles not to become the world's backwater with high inequalities predominantly between but also within countries.

The core set of climate models related to RCP8.5 project high to very high change until 2100, depending on the selected climate model. This translates into strong changes in average annual temperature of 3-5^{o}C across Europe, with in general higher values for Scandinavia and lower values for the UK, but with maximum values of up to close to 10°C locally. Average annual precipitation values likewise change strongly towards 2100. In general, changes are relatively small for western and central Europe. Particularly dramatic are decreases across the Mediterranean of up to 50% less rainfall in summer. Strong changes in rainfall also occur in the Nordic countries with increases of up to 70% in winter. Overall, climate change is very strong and will pose high challenges.

Impact model runs with the IAP2 illustrate how this climate change results in strong changes in some of the key indicators. Combined changes in climate and socio-economics lead to a dramatic decrease in the area of extensive grassland, while potential carbon stocks strongly increase and the water exploitation index also increases significantly. Model runs furthermore show large spatial variability in climate change impacts in SSP3.

When stakeholders adjusted SSP3 based on the RCP8.5 climate change scenario, they argue that climate change impacts would significantly worsen the outlook of many sectors and factors. Induced socio-economic change and ability to adapt are likely to be rather small as societies are vulnerable with high challenges to mitigation and adaptation. Extreme weather events act as catalysts, accelerating negative developments with migration and poverty worsening.

SSP3 is furthermore characterised by multiple tipping elements that happen at various moments in time. Notable are strong socio-economic changes (breakdown of the EU; disintegration of social fabric), but these are coupled with many potential climatic tipping elements (slow-down of AMOC; disappearing of permafrost; etc.). Although the combined impact is unknown, it is likely to be strong with either windows of opportunity (for new actors) or destruction (when multiple tipping points are reached simultaneously).

A fatalist worldview dominates in the stories across all case studies, associated with a lack of effective multi-scale decision-making. Failing policy measures and unfavorable external circumstances are other common elements across scale. Actors are either incapable of organisation at all (Hungary), or organise in local informal communities (Scotland), or attempt to organise regionally at the large scale (Iberia and Europe). Ultimately, the different reactions of local actors to the overall unfavourable socio-economic and climate conditions determines whether some individualist or egalitarian worldviews are present.

In all case studies the level of actor capacities is very low except for the European and Scottish scenarios where unlocking capacity becomes higher, i.e. where communities of interest are established. This provides some stability and decreases conflict, albeit with larger inequalities than at present. This unlocking capacity holds a promise of bottom-up improvements.

In short, an integrated RCP8.5 × SSP3 future outlook is one of disintegration of social fabric and many countries struggling to maintain living standards, while Europe struggles not to become the world's backwater with high inequalities. At the same time climate change hits hard with strong increases in temperature and strong decreases and increases in precipitation, and related floods and droughts. Climate change impacts would significantly worsen the outlook of many sectors and factors, while society's ability to adapt or mitigate is low. Moreover, there are many potential tipping elements that might further worsen future prospects. On the other hand, models runs show that key indicators are not all changing in the wrong direction with a much higher potential to store carbon. More importantly, with the disappearance of current dominant governance models, unlocking capacities of newly formed (local) networks increase, which makes this integrated scenario a potential starting point for new beginnings.

4.6.3. RCP4.5 × SSP4

The SSP4 story is that, globally, power becomes more concentrated in a relatively small political and business elite, accompanied by increasing disparities in economic opportunity. This leads to substantial proportions of populations having a low level of development, although Europe becomes an important player in a world full of tensions. Sparked by the economic crisis and extreme weather events, the EU increases commitment to find innovative solutions to the depletion of natural resources and climate change. In combination with current relatively high levels of social cohesion, energy efficiency and environmental policy-making this initiates a shift towards a high-tech green Europe. This transformation is strongly supported by large businesses that successfully seek collaboration with the increasingly powerful European government. At the same time, however, inequalities are rising because of a number of simultaneously acting factors, including highly unequal investments in education. This leads to a large and widening gap between an internationally-connected society and a more fragmented collection of lower-income societies that work in a labour intensive, low-tech economy. Technological development has not resulted in reduced energy prices, but has instead established an oligarchy of green business developers that control energy supply. By 2100, Europe is an important player in a world full of tensions, but with growing inequalities across and within European countries.

The core set of climate models related to RCP4.5 projects low to intermediate change until 2100, depending on the selected climate model. This nevertheless translates into considerable changes in average annual temperatures of 2.5-3.5^{o}C, with in general higher values for Scandinavia and lower values for the UK, and with minimum values of 0.7^{o}C and maximum values of up to 6^{o}C. Average annual precipitation values likewise change considerably towards 2100. With more spread between the different core models, average annual precipitation is projected to increase strongly in Scandinavia (up to +30-35%); moderately in mainland Europe (+5-15%); and decrease in the Mediterranean (up to -25%). Overall, climate change poses considerable challenges.

Impact model runs with the IAP2 have not been analysed in detail in the context of this scenario integration exercise, but show similar tendencies as for SSP1 with increases in water stress (as indicated by the water exploitation index) and potential carbon stocks, and decreases in the area of extensive grassland. In general, the climate impact signal related to key indicators seems relatively strong. Model runs furthermore show considerable spatial variability in climate change impacts in SSP3.

When stakeholders adjusted SSP4 based on the RCP4.5 climate change scenario, the impact of climate change on socio-economic change was considered to be relatively small, as this is a scenario with less severe climate change (than RCP8.5) and a green elite that can act quickly and mitigate successfully when needed.

SSP4 is furthermore characterised by multiple tipping elements that happen at various moments in time. These are mostly socio-economic (behavioural change; shift in energy sector) but might also include climatic tipping elements (melting of Greenland ice sheet and Alpine glaciers).

The SSP4 stories share strong common elements across all case studies with strong regulatory top-down societies mostly related to a hierarchist worldview. However, unlike SSP1, the hierarchist worldview has to be understood together with a fatalist worldview, with high social and economic inequalities. This is the backbone of the stories in all case studies.

The combination of top-down regulation in an unequal society is reflected also in levels of capacities of actors: high capacity for national or European level actors and a low capacity for local actors. In most case studies, a mix of economic and political actors exert a stabilising influence. However, competition, political and economic power grabbing, and large-scale social exclusion limit the increase of capacities in all case studies. There is a rigid top-down maintenance of the status quo throughout the whole scenario, *de facto* decreasing the potential of local actors.

In short, an integrated RCP4.5 × SSP4 5 future outlook is one where power becomes more concentrated in a relatively small political and business elite, accompanied by increasing disparities, but where Europe becomes an important player in a world full of tensions. Climate change poses considerable challenges, but impacts are largely ignored (when affecting the masses) or can be effectively dealt with (for the elite), also when tipping points are reached, as the elite has a high capacity to react quickly when needed, even while other capacities are limited and decreasing.

4.6.4. RCP8.5 × SSP5

The story of SSP5 is that people in this world place increasing faith in competitive markets, innovation and participatory societies to produce rapid technological progress and development of human capital as the path to sustainable development. A lack of environmental concern leads to the exploitation of abundant fossil fuel resources. Global markets are increasingly integrated, with interventions focused on removing institutional barriers. There are also strong investments in health, education, and institutions to enhance human and social capital. The push for economic and social development is coupled with the exploitation of abundant fossil fuel resources, including large-scale extraction of shale gas. This further stimulates economic wealth, part of which is used to stimulate the development of (green) technologies. Europe regains its leading position in the global economy. Faith is strong in the ability to effectively manage social and ecological systems, including by geo-engineering. Population across all societal classes adopts a very energy intensive lifestyle. The environment degrades, but the majority of the population is unaware because of successful technological innovation. Towards 2100, the environment is locally seriously degraded as non-renewables are further exploited, which eventually results in a slow re-emergence of investments in renewables.

The core set of climate models related to RCP8.5 project high to very high change until 2100, depending on the selected climate model. This translates into strong changes in average annual temperature of 3-5^{o}C across Europe, with in general higher values for Scandinavia and lower values for the UK, but with maximum values of up to close to 10^{o}C locally. Average annual precipitation values likewise change strongly towards 2100. In general, changes are relatively small for western and central Europe. Particularly dramatic are decreases across the Mediterranean of up to 50% less rainfall in summer. Strong changes also occur in the Nordic countries with increases up to 70% in winter. Overall, climate change is very strong and will pose high challenges.

Impact model runs with the IAP2 have not been analysed in detail in the context of this scenario integration exercise, but show very strong increases in water stress (as indicated by the water exploitation index) due to the high levels of climate change, strong decreases in extensive grassland, and increases in potential carbon stocks. In general, the mix of strong technological change in SSP5 coupled with strong climate change results in changes in key indicators that are partly dissimilar from trends in the other scenarios. Model runs furthermore show strong spatial variability in climate change impacts in SSP5.

When stakeholders adjusted SSP5 based on the RCP8.5 climate change scenario, they discussed the serious consequences of climate change in a socio-economic future that has high social and human capital. It was argued that substantial measures would be taken to adapt to climate change, but also to mitigate emissions. Most of the changes would happen around 2050; particularly investments in green technologies would happen much earlier due to climate change (impacts). Stakeholders uncovered the tension between a strong society with low challenges to adapt, but failing to mitigate, which were not completely accepted as plausible.

Similarly, SSP5 is characterised by positive and negative tipping elements. Rapid progress in all major sectors and improvement of education and health care happens while the environment is seriously degraded, coupled with many potential climatic tipping elements (slow-down of AMOC; disappearance of permafrost; etc.). Although the combined impact is unknown, it is likely to be strong with potential implications on the willingness and necessity to act and/or mitigate.

A comparison across the case studies demonstrates that SSP5 is very heterogeneous and highly dependent on the socio-cultural context and the scales involved in the analysis. The individualist perspective is dominant with a belief that economic and technological development are most important values and technology will solve environmental degradation. This is associated with hierarchist perspectives with strong top-down institutions, or multinational dominance. With the change in perception related to environmental degradation, a shift towards the opposite (fatalist and egalitarian worldviews) is observed. In cases where overall perception does not change, individualism tends to remain dominant, albeit with less support or less effective control and more space to increasing (fatalist) perception towards environmental governance problems (European case study).

The closer the shift towards fatalism, the lower overall actors' capacities, especially in the Hungarian and Iberia local case studies. However, when large-scale environmental destruction becomes apparent later in the scenario, unlocking capacity increases with increased societal awareness and an effective challenge to the established top-down governance. This is the case for the Scottish and Iberian case studies towards 2100.

In short, an integrated RCP8.5 × SSP5 future outlook is one where people place increasing faith in competitive markets and innovation to produce rapid technological progress and development of human capital. Towards 2100, the environment is seriously degraded as non-renewables are over-exploited. At the same time climate change hits hard with strong increases in temperature and strong decreases and increases in precipitation, and related floods and droughts, and large-scale tipping points. Impacts on society are nonetheless minor because of technological innovation and the ability to manage ecosystems. It is likely that climate change impacts in a strong society such as in SSP5 might trigger substantial measures to be taken to adapt to climate change, but also to mitigate emissions, perhaps as early as 2050, also because of increasing actors' capacities. Local-scale stories show similar tensions of unabated climate change impacts and environmental destruction in an educated, participatory society that takes a reactive attitude for 80 years.

5. Conclusions and recommendations

This concluding section provides (methodological) recommendations on where to focus on further improving the integration of climate and socio-economic scenarios.

Overall:

- **A wealth of innovative methods and resulting (integrated) scenarios have been produced**. The IMPRESSIONS scenario development efforts have produced a wealth of methodological innovations; new and better socio-economic and climate scenarios; and multiple insights into issues when integrating SSPs and RCPs. Scenario development efforts have advanced the state-of-the-art.
- **The set of four SSPs and two RCPs was sufficient to create a diverse set of high-end integrated scenarios.** Both the selected RCPs and the SSPs proved to present rather extreme future outlooks. Particularly the long time horizon of 2100 caused all SSPs to tell stories of strong change, including tipping elements, breakdown of societies, energy transitions etc. Likewise, the RCPs translated into (strong) climate change impacts.
- **More use needs to be made of the method that was developed in IMPRESSIONS.** In essence, the method of using RCPs × SSPs, participatory methods, (climate and impact) models, etc. needs to be used in other settings and scales.

On analysing cross-scale integration of scenarios:

- **The purpose of socio-economic scenarios changes the conclusions on cross-scale comparability**. When the focus is on key model parameters (e.g. population growth) conclusions on what is comparable and scalable is different from when the focus is on contextualising actor capacities or worldviews in the basic stories. For example, inconsistencies between model assumptions, storyline assumptions, and parameter estimates by stakeholders surface in SSP1 – the scenario that is otherwise characterised by being very similar across scales. Similarly, small differences in the basic story of SSP4 hide large differences in assumptions on key drivers such as economic development.
- **Climate scenario scaling methods have received more attention than socio-economic methods**. Scaling methods of socio-economic scenarios are in need of more structural testing and further development, also given the diversity of approaches, methods, and purposes.

On tipping elements:

- **It proved difficult to identify both socio-economic and climatic tipping elements, and close to impossible to integrate them**. Despite ample experience in earlier endeavours, also documented in the literature, it proved difficult to operationalise the concept of “tipping points” related to the scenarios developed in IMPRESSIONS. Even when using the more ‘modest’ term of “tipping element” (to indicate that we know what is tipping, but not when or with what threshold), it was difficult to provide a clear list.
- **Even poorly defined, it is clear that “tipping elements” will occur and that socio-economic and climatic tipping elements can have combined reinforcing effects.** Comparing potential climatic and socio-economic tipping elements, it is clear that for example in SSP3 combined effects could be disastrous. Stakeholders clearly indicated that extreme climatic events could trigger strong socio-economic change, thus hinting towards positive tipping elements.

On integration:

- **Using models to integrate scenarios might overestimate the climate signal**. Although not based on an exhaustive analysis, the analysis here shows that when using quantitative models, climate change has a larger influence in integrated runs. This needs to be studied in more detail, as it contradicts more exhaustive analyses using the IAP2 (e.g. Harrison et al., 2018 and Deliverable D3.2 – Nowak et al., 2018).
- **Using stories to integrate scenarios might overestimate the socio-economic signal.** Similarly based on a small sample without exhaustive analysis, there are indications that when using SSP stories as the integrator, the climate change impacts are underrepresented in the final product. This also needs to be studied in more detail.
- **Using mixed methods when integrating socio-economic and climate scenarios is essential.** Based on the first two points, it is clear that different methods lead to different conclusions on what is the effect of integrating scenarios. Particularly the use of stories as a starting point deserves more analysis.
- **Within a toolbox of integrating methods, models are and should remain a main tool for integration**. Integrated models such as the IAP2 should be (and are being) further developed. An essential improvement could be a more explicit, more structured, and more transparent inclusion of the interaction between climate and socio-economic factors. Essential is also the improvement of the temporal dynamics of the interactions between multiple drivers across multiple sectors as in the rIAM (see Deliverable D3B.2 – Holman et al., 2017).
- **Development of pathways underutilises climate information**. Although not analysed here, we recommend to develop methods to improve the incorporation of climate change and climate change impacts in pathways, which now seem mostly based on socio-economic capacities and capitals.

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