The Shared Socioeconomic Pathways and their Energy, Land Use, and Greenhouse Gas Emissions Implications: An Overview

Draft submitted to Global Environmental Change on 15 December 2015
Accepted: 24 May 2016

Authors:
Keywan Riahi*[1], Detlef P. van Vuuren[2], Elmar Kriegler[3], Jae Edmonds[4], Brian O'Neill[5], Shinichiro Fujimori[6], Nico Bauer[3], Katherine Calvin[4], Rob Dellink[7], Oliver Fricko[1], Wolfgang Lutz[1], Alexander Popp[3], Jesus Crespo Cuaresma[1], Samir KC[1,8], Marian Leimbach[3], Leiwen Jiang[5], Tom Kram[2], Shilpa Rao[1], Johannes Emmerling[9,10], Kristie Ebi[11], Tomoko Hasegawa[6], Petr Havlik[1], Florian Humpenöder[3], Lara Aleluia Da Silva[9,10], Steve Smith[4], Elke Stehfest[2], Valentina Bosetti[9,10,12], Jiyong Eom[4,13], David Gernaat[2], Toshihiko Masui[6], Joeri Rogelj[1], Jessica Strefler[3], Laurent Drouet[9,10], Volker Krey[1], Gunnar Luderer[3], Mathijs Harmsen[2], Kiyoshi Takahashi[6], Lavinia Baumstark[3], Jonathan Doelman[2], Mikiko Kainuma[6], Zbigniew Klimont[1], Giacomo Marangoni[9,10], Hermann Lotze-Campen[3], Michael Obersteiner[1], Andrzej Tabeau[14], Massimo Tavoni[9,10,15]

Affiliations:
[1]International Institute for Applied Systems Analysis, Laxenburg, Austria
[2]PBL Netherlands Environmental Assessment Agency, Bilthoven, Netherlands
[3]Potsdam Institute for Climate Impact Research, Telegrafenberg A31, 14473 Potsdam, Germany
[4]Pacific Northwest National Laboratory, Joint Global Change Research Institute at the University of Maryland-College Park, College Park, MD, United States
[5]National Center for Atmospheric Research (NCAR), 1850 Table Mesa Drive, Boulder, CO, United States
[6]National Institute for Environmental Studies (NIES), Tsukuba, Japan
[7]The Organisation for Economic Co-operation and Development (OECD), Paris, France
[8]Asian Demographic Research Institute, Shanghai University, Shanghai, China[9]Fondazione Eni Enrico Mattei (FEEM), Milan, Italy
[10]Centro Euro-Mediterraneo sui Cambiamenti Climatici, Italy
[11]School of Public Health, University of Washington, Seattle, United States
[12]Bocconi University, Department of Economics, Italy
[13]KAIST College of Business, Seoul, Republic of South Korea
[14]Landbouw Economisch Instituutm, Wageningen University and Research Centre, Netherlands
[15]Politecnico di Milano, Department of Management and Economics, Italy

*Corresponding author
Email: riahi@iiasa.ac.at
Phone: ++43 676 83807491

Abstract

This paper presents the overview of the Shared Socioeconomic Pathways (SSPs) and their energy, land use, and emissions implications. The SSPs are part of a new scenario framework, established by the climate change research community in order to facilitate the integrated analysis of future climate impacts, vulnerabilities, adaptation, and mitigation. The pathways were developed over the last years as a joint community effort and describe plausible major global developments that together would lead in the future to different challenges for mitigation and adaptation to climate change. The SSPs are based on five narratives describing alternative socio-economic developments, including sustainable development, regional rivalry, inequality, fossil-fueled development, and a middle-of-the-road development. The long-term demographic and economic projections of the SSPs depict a wide uncertainty range consistent with the scenario literature. A multi-model approach was used for the elaboration of the energy, land-use and the emissions trajectories of SSP-based scenarios. The baseline scenarios lead to global energy consumption of 500-1100 EJ in 2100, and feature vastly different land-use dynamics, ranging from a possible reduction in cropland area up to a massive expansion by more than 700 million hectares by 2100. The associated annual CO_2 emissions of the baseline scenarios range from about 25 $GtCO_2$ to more than 120 $GtCO_2$ per year by 2100. With respect to mitigation, we find that associated costs strongly depend on three factors: 1) the policy assumptions, 2) the socio-economic narrative, and 3) the stringency of the target. The carbon price for reaching the target of 2.6 W/m^2 differs in our analysis thus by about a factor of three across the SSP scenarios. Moreover, many models could not reach this target from the SSPs with high mitigation challenges. While the SSPs were designed to represent different mitigation and adaptation challenges, the resulting narratives and quantifications span a wide range of different futures broadly representative of the current literature. This allows their subsequent use and development in new assessments and research projects. Critical next steps for the community scenario process will, among others, involve regional and sectorial extensions, further elaboration of the adaptation and impacts dimension, as well as employing the SSP scenarios with the new generation of earth system models as part of the 6th climate model intercomparison project (CMIP6).

1. Introduction

Scenarios form an essential part of climate change research and assessment. They help us to understand long-term consequences of near-term decisions, and enable researchers to explore different possible futures in the context of fundamental future uncertainties. Perhaps most importantly, scenarios have been crucial in the past for achieving integration across different research communities, e.g., by providing a common basis for the exploration of mitigation policies, impacts, adaptation options and changes to the physical Earth system. Prominent examples of such scenarios include earlier scenarios by the Intergovernmental Panel on Climate Change (SA90, IS92, and SRES) and the more recent Representative Concentration Pathways (RCPs) (Moss et al., 2010; van Vuuren et al., 2011). Clearly, such 'community' scenarios need to cover many aspects: they need to describe different climate futures, but ideally also cover different possible and internally consistent socioeconomic developments. Research has shown that the latter may be just as important for climate impacts and adaptation possibilities as for mitigation options (Field et al., 2014; Morita et al., 2000).

Moss et al. (2010) described the "parallel process" of developing new scenarios by the climate research community. This process includes the Representative Concentration Pathways (RCPs), which cover the climate forcing dimension of different possible futures (van Vuuren et al., 2011), and served as the basis for the development of new climate change projections assessed in the IPCC Fifth Assessment Report (IPCC, 2013; Taylor et al., 2012). Based on two main initial proposals by Kriegler et al. (2012) and van Vuuren et al. (2012), the design of the socioeconomic dimension of the scenario framework was also established (Ebi et al., 2014; Kriegler et al., 2014a; O'Neill et al., 2014; van Vuuren et al., 2014). The new framework combines so-called Shared Socioeconomic Pathways (SSPs) and the RCPs (and other climate scenarios) in a Scenario Matrix Architecture.

This article is the overview paper of a Special Issue on the SSPs where we describe critical subsequent steps to make the framework operational. Elaborate descriptions of the different SSP elements are summarized in fourteen other articles in this special issue complementing this overview paper. To this end, we present new SSP narratives (O'Neill et al., 2016a) and associated quantitative descriptions for key scenario drivers, such as population (KC and Lutz, 2016), economic growth (Crespo Cuaresma, 2016; Dellink et al., 2016; Leimbach et al., 2016), and urbanization (Jiang and O'Neill, 2016). These projections and their underlying narratives comprise the basic elements of the SSPs and have been further used for the development of integrated scenarios, which elaborate the SSPs in terms of energy system and land-use changes (Bauer et al., submitted; Popp et al., submitted) as well as resulting air pollutant (Rao et al., submitted) and greenhouse gas emissions and atmospheric concentrations. A detailed discussion of integrated scenarios for the individual SSPs (Calvin et al., submitted; Fricko et al., submitted; Fujimori et al., submitted; Kriegler et al., submitted; van Vuuren et al., submitted) complement the special issue.

The SSPs and the associated scenarios presented here are the result of an iterative community process, leading to a number of important updates during the last three years. Considerable attention was paid during the design phase to ensure consistency between the different elements. By providing an integrated description - both in terms of the qualitative narratives as well as the quantitative projections - this paper aims at providing a broad overview of the main SSP results.

The process of developing the SSPs and IAM scenarios involved several key steps. First, the narratives were designed and subsequently translated into a common set of “input tables”, guiding the quantitative interpretation of the key SSP elements and scenario assumptions (e.g., on resources availability, technology developments and drivers of demand such as lifestyle changes – see O’Neill et al. (2016a) and Appendix A of the Supplementary Material). Second, the narratives were translated into quantitative projections for main socioeconomic drivers, i.e. population, economic activity and urbanization. Finally, both the narratives and the associated projections of socio-economic drivers were elaborated using a range of integrated assessment models in order to derive quantitative projections of energy, land use, and emissions associated with the SSPs.

For the quantitative projections of economic growth and the integrated energy-land use-emissions scenarios, multiple models were used, which provided alternative interpretations of each of the SSPs. Among these interpretations so-called “marker” SSPs were selected as representative of the broader developments of each SSP. The selection of markers was guided by two main considerations: the internal consistency of the full set of SSP markers, and the ability of the different models to represent distinct characteristics of the storylines. Identifying the markers involved an iterative process with multiple rounds of internal and external reviews. The process helped to ensure that marker scenarios were particularly scrutinized in terms of their representativeness for individual SSPs and that the relative differences between models were well represented in the final set of SSP markers. It is important to note that while the markers can be interpreted as representative of a specific SSP development, they are not meant to provide a central or median estimate. The “non-marker” scenarios are important, since they provide insights into possible alternative scenario interpretations of the same basic SSP elements and storylines, including a first-order estimate of the (conditional) uncertainties attending to model structure and interpretation/implementation of the storylines. In addition, the non-marker scenarios help to understand the robustness of different elements of the SSPs (see also section 7, below). An important caveat, however, is that the SSP uncertainty ranges are often based on different sample sizes, as not all modelling teams have so far developed a scenario for each of the SSPs. Note also that our results should not be regarded as a full representation of the underlying uncertainties. The results are based on a relatively limited number of three models for the GDP projections and six models for the IAM scenarios. Additional models or other variants of the SSP narratives would influence some of our results. As part of future research, additional SSP scenarios are expected to be generated by a wide range of IAMs to add further SSP interpretations. This will further increase the robustness of uncertainty ranges for individual SSPs and estimates of differences between SSPs.. The set of results comprises quantitative estimates for population, economic growth, energy system parameters, land use, emissions, and concentrations. All the data are publicly available through the interactive SSP web-database at https://secure.iiasa.ac.at/web-apps/ene/SspDb.

The current set of SSP scenarios consists of a set of baselines, which provides a description of future developments in absence of new climate policies beyond those in place today, as well as mitigation scenarios which explore the implications of climate change mitigation policies. The baseline SSP scenarios should be considered as reference cases for mitigation, climate impacts and adaptation analyses. Therefore, and similar to the vast majority of other scenarios in the literature, the SSP scenarios presented here do not consider feedbacks from the climate system on its key drivers such as socioeconomic impacts of climate change. The mitigation scenarios were developed focusing on the forcing levels covered by the RCPs. The resulting combination of SSPs with RCPs constitutes a first comprehensive application of the scenario matrix (van Vuuren et al., 2014) from the perspective of emissions mitigation (Section 6.3). Importantly, the SSPs and the associated scenarios presented here are only meant as a starting point for the application of the new scenario framework in climate change research. Important next steps will be the analysis of climate impacts and adaptation, the adoption of SSP emissions scenarios in the next round of climate change projections and the exploration of broader sustainability implications of climate change and climate policies under the different SSPs.

In the remainder of the paper we first describe in Section 2 the methods of developing the SSPs in more detail. Subsequently, Section 3 presents an overview of the narratives. The basic SSP elements in terms of key scenario driving forces for population, economic growth and urbanization are discussed in Section 4. Outcomes for energy, land-use change and the resulting emissions in baseline scenarios are presented in Section 5, while Section 6 focuses on the SSP mitigation scenarios. Finally, Section 7 concludes and discusses future steps in SSP research.

2. Methods

2.1 Basic elements and baseline scenarios

The SSPs have been developed to provide five distinctly different pathways about future socioeconomic developments as they might unfold in the absence of explicit additional policies and measures to limit climate forcing or to enhance adaptive capacity. They are intended to enable climate change research and policy analysis, and are designed to span a wide range of combinations of challenges to mitigation and adaptation to climate change. The resulting storylines, however, are broader than these dimensions alone – and in fact some of their elements nicely align with scenarios from earlier exercises in the past (Nakicenovic and Swart, 2000; van Vuuren and Carter, 2014).

The development of the SSPs comprised five main steps as illustrated in Figure 1:

- Design of the *narratives*, providing the fundamental underlying logic for each SSP, focusing also on those elements of socioeconomic change that often cannot be covered by formal models.
- *Extensions of the narratives* in terms of model “input tables”, describing in qualitative terms the main SSP characteristics and scenario assumptions.
- Elaboration of the basic elements of the SSPs in terms of *demographic and economic drivers* using quantitative models.
- Elaboration of developments in the energy system, land use and greenhouse gas and air pollutant emissions of the *SSP baseline scenarios* using a set of Integrated Assessment Models (IAMs)
- Elaboration of these elements by IAMs for the *SSP mitigation scenarios*.

The narratives of the SSPs (O'Neill et al., 2016a) were developed using large expert teams that together designed the storylines and ensured their internal consistency. Similarly, different interdisciplinary groups of experts (5-10 people) participated in the development of the model input tables, ensuring sufficient discussion on the interpretation of the different elements (see, e.g., O’Neill et al. (2016a), KC and Lutz (2016), and Appendix A and E of the Supplementary Material).

For each SSP, a single population, education (KC and Lutz, 2016) and urbanization projection (Jiang and O'Neill, 2016) was developed, while three different economic modeling teams participated in the development of the GDP projections (Crespo Cuaresma, 2016; Dellink et al., 2016; Leimbach et al., 2016). The GDP projections by Dellink et al. were selected as the representative ‘marker’ SSP projections. As a next step, the IAM models used the marker GDP and population projections as quantitative inputs for developing the SSP scenarios. Six alternative IAM models were used for the quantification of the SSP baseline scenarios. For each SSP a single IAM interpretation was selected as the so-called representative marker scenario for recommended use by future analyses of climate change, its impacts and response measures (recognizing that often the full space of available scenarios cannot be analyzed). In addition to the marker scenario, each SSP was interpreted by other IAM models, leading to multiple non-marker IAM scenarios for each SSP narrative. The multi-model approach was important for understanding the robustness of the results and the (conditional) uncertainties associated with the different SSPs.

Differences between the full set of SSP scenarios include those that are attributable to differences across the underlying narratives, differences in the quantitative interpretation of a given narrative, and differences in IA model structure. For a given SSP, it is useful to have a variety of different quantitative scenarios, since they help to highlight the range of uncertainty that attends to model structures and different interpretations of SSPs. Similarly, SSP scenarios derived from a single IAM helps highlight differences due to variation of the SSP input assumptions alone (see, e.g., the marker papers listed in Table 1). In sum six IAM models participated in the scenario development and five models provided the associated marker scenarios of the five SSPs (see Table 1). Finally, the GHG and aerosol emissions from the IAM models were used in the simple climate model MAGICC-6 (Meinshausen et al., 2011a; Meinshausen et al., 2011b) in order to provide insights into possible consequences for concentrations and related climate change. More documentation on the model systems used in this paper can be found in Appendix D of the Supplementary Material).

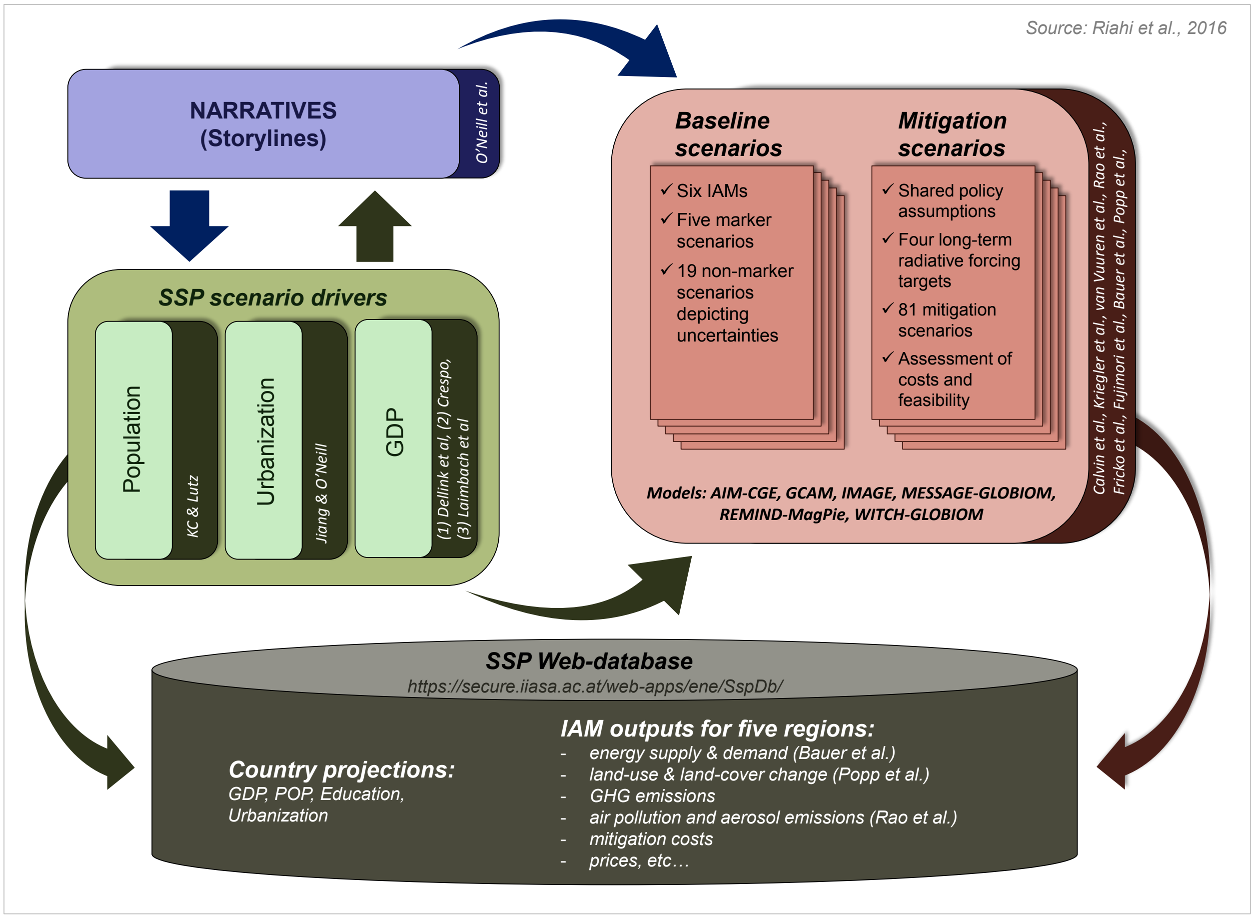

Figure 1: Schematic illustration of main steps in developing the SSPs, including the narratives, socioeconomic scenario drivers (basic SSP elements), and SSP baseline and mitigation scenarios.

Table 1: IAM models and their use for the development of the SSP scenarios (for further details on SSP scenarios by model see also Table 2 of the Supplementary Material)

Model name (hosting institution)	SSP Marker	SSP coverage (# of scenarios)	Model category	Solution Algorithm
AIM/CGE (NIES)	SSP3 (Fujimori et al., submitted)	SSP1, SSP2, SSP3, SSP4, SSP5 (22 scenarios)	General equilibrium (GE)	Recursive dynamic
GCAM (PNNL)	SSP4 (Calvin et al., submitted)	SSP1, SSP2, SSP3, SSP4, SSP5 (20 scenarios)	Partial equilibrium (PE)	Recursive dynamic
IMAGE (PBL)	SSP1 (van Vuuren et al., submitted)	SSP1, SSP2, SSP3, (13 scenarios)	Hybrid (systems dynamic model and GE for agriculture)	Recursive dynamic
MESSAGE-GLOBIOM (IIASA)	SSP2 (Fricko et al., submitted)	SSP1, SSP2, SSP3, (13 scenarios)	Hybrid (systems engineering partial equilibrium models linked to aggregated GE)	Intertemporal optimization

REMIND-MAgPIE (PIK)	SSP5 (Kriegler et al., submitted)	SSP1, SSP2, SSP5, (14 scenarios)	General equilibrium (GE)	Intertemporal optimization
WITCH-GLOBIOM (FEEM)	-	SSP1, SSP2, SSP3, SSP4, SSP5 (23 scenarios)	General equilibrium (GE)	Intertemporal optimization

2.2 Development of mitigation scenarios

We use the baseline SSP scenarios as the starting point for a comprehensive mitigation analysis. To maximize the usefulness of our assessment for the community scenario process, we select the nominal RCP forcing levels of 2.6, 4.5, and 6.0 W/m^2 in 2100 as the long-term climate targets for our mitigation scenarios. A key reason for selecting these forcing levels is to provide a link between the SSPs and the RCPs developed in the initial phase of the community scenario process. Establishing this link is important as it will enable the impacts, adaptation and vulnerability (IAV) community to use the information on the SSPs in conjunction with the RCP climate projections archived in the CMIP5 data base (Taylor et al., 2012). We thus try to get as close as possible to the original RCP forcing pathways, which sometimes deviate slightly from the 2100 forcing level indicated by the RCP-label (see Section 2 and Section 5 of the Supplementary Material). In addition, we explore mitigation runs for a target of 3.4 W/m^2. This intermediate level of radiative forcing (approximately 550 ppm CO_2-e) is located between very stringent efforts to reduce emissions given by RCP2.6 (approximately 450 ppm CO_2-e) and less stringent mitigation efforts associated with RCP4.5 (approximately 650 ppm CO_2-e). Exploring the level of 3.4 W/m^2 is particularly policy-relevant, considering, for example, recent discussions about scenarios and the attainability of the 2°C objective, which is broadly in line with scenarios aiming at 2.6 W/m^2 (Kriegler et al., 2015; Kriegler et al., 2014b; Riahi et al., 2015; Victor and Kennel, 2014). On the other hand, recent developments in international climate policy (e.g., the newly adopted Paris Agreement under the United Nations Framework Convention on Climate Change) have renewed attention to the importance of exploring temperature levels even lower than 2°C, in particular a long term limit of 1.5°C. These developments were too recent to be taken up already, but are considered in forthcoming work.

Finally, since policies and their effectiveness can be expected to vary consistent with the underlying socioeconomic storylines, we define so-called Shared Policy Assumptions: SPAs (Kriegler et al., 2014a). The SPAs describe the climate mitigation policy environment for the different SSPs. They are discussed in more detail in Section 6 of the paper (and the Appendix B and Section 6 of the Supplementary Material).

3. SSP Narratives

The SSP narratives (O'Neill et al., 2016a) comprise a textual description of how the future might unfold in terms of broad societal trends. Their main purpose is to provide an internally consistent logic of the main causal relationships, including a description of trends that are traditionally difficult to capture by models. In this sense, the SSP narratives are an important complement to the quantitative model projections. By describing major socioeconomic, demographic, technological, lifestyle, policy, institutional and other trends, the narratives add important context for a broad user community to better understand the foundation and meaning of the quantitative SSP projections. At the same time, the narratives have been a key input into the modeling process, since they underpin the quantifications and guided the selection of assumptions for the socioeconomic projections and the SSP energy and land-use transitions described in this special issue.

Consistent with the overall scenario framework , the narratives are designed to span a range of futures in terms of the socioeconomic challenges they imply for mitigating and adapting to climate change. Two of the SSPs describe futures where challenges to adaptation and mitigation are both low (SSP1) or both high (SSP3). In addition, two “asymmetric cases” are designed, comprising a case in which high challenges to mitigation is combined with low challenges to adaptation (SSP5), and a case where the opposite is true (SSP4). Finally a central case describes a world with intermediate challenges for both adaptation and mitigation (SSP2).

In Table 2 we provide a short summary of the global narratives, which have been used throughout all the papers of this special issue. O’Neill et al. (2016a) provides a more detailed description and discussion of the narratives. In addition, the Supplementary Material (Section 4 and Appendix A) includes specific descriptions of how the global narratives were extended to provide further guidance on scenario assumptions concerning energy demand and supply, technological change, and land-use changes.

While the SSPs employ a different scenario design and logic compared to earlier IPCC scenarios, such as the SRES scenarios (Nakicenovic and Swart, 2000), their narratives as well as some of their scenario characteristics show interesting similarities. Analogies between the SRES scenarios and the SSPs were identified already during the SSP development phase (Kriegler et al., 2012; O’Neill et al., 2014), and a systematic attempt to map the SSPs to SRES and other major scenarios was conducted by van Vuuren and Carter (2014). They find that particularly the “symmetric” SSPs (where both the challenges to mitigation and to adaptation are either high or low) show large similarities to some of the SRES scenario families. For example, there is a clear correspondence between the sustainability focused worlds of SSP1 and SRES B1. Similarly, the fragmented world of SRES A2 shares many scenario characteristics with SSP3, which is describing a world dominated by regional rivalry. The middle-of-the-road scenario SSP2 corresponds well to the dynamics-as-usual scenario SRES B2. And finally, SSP5 shares many storyline elements with the A1FI scenario of SRES, both depicting high fossil-fuel reliance and high economic growth leading to high GHG emissions. For further details about the mapping of the SSPs and earlier scenarios see van Vuuren and Carter (2014).

Table 2: Summary of SSP Narratives

SSP1	**Sustainability – Taking the Green Road (Low challenges to mitigation and adaptation)** *The world shifts gradually, but pervasively, toward a more sustainable path, emphasizing more inclusive development that respects perceived environmental boundaries. Management of the global commons slowly improves, educational and health investments accelerate the demographic transition, and the emphasis on economic growth shifts toward a broader emphasis on human well-being. Driven by an increasing commitment to achieving development goals, inequality is reduced both across and within countries. Consumption is oriented toward low material growth and lower resource and energy intensity.*
SSP2	**Middle of the Road (Medium challenges to mitigation and adaptation)** *The world follows a path in which social, economic, and technological trends do not shift markedly from historical patterns. Development and income growth proceeds unevenly, with some countries making relatively good progress while others fall short of expectations. Global and national institutions work toward but make slow progress in achieving sustainable development goals. Environmental systems experience degradation, although there are some improvements and overall the intensity of resource and energy use declines. Global population growth is moderate and levels off in the second half of the century. Income inequality persists or improves only slowly and challenges to reducing vulnerability to societal and environmental changes remain.*
SSP3	**Regional Rivalry – A Rocky Road (High challenges to mitigation and adaptation)** *A resurgent nationalism, concerns about competitiveness and security, and regional conflicts push countries to increasingly focus on domestic or, at most, regional issues. Policies shift over time to become increasingly oriented toward national and regional security issues. Countries focus on achieving energy and food security goals within their own regions at the expense of broader-based development. Investments in education and technological development decline. Economic development is slow, consumption is material-intensive, and inequalities persist or worsen over time. Population growth is low in industrialized and high in developing countries. A low international priority for addressing environmental concerns leads to strong environmental degradation in some regions.*
SSP4	**Inequality – A Road Divided (Low challenges to mitigation, high challenges to adaptation)** *Highly unequal investments in human capital, combined with increasing disparities in economic opportunity and political power, lead to increasing inequalities and stratification both across and within countries. Over time, a gap widens between an internationally-connected society that contributes to knowledge- and capital-intensive sectors of the global economy, and a fragmented collection of lower-income, poorly educated societies that work in a labor intensive, low-tech economy. Social cohesion degrades and conflict and unrest become increasingly common. Technology development is high in the high-tech economy and sectors. The globally connected energy sector diversifies, with investments in both carbon-intensive fuels like coal and unconventional oil, but also low-carbon energy sources. Environmental policies focus on local issues around middle and high income areas.*
SSP5	**Fossil-fueled Development – Taking the Highway (High challenges to mitigation, low challenges to adaptation)** *This world places 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. Global markets are increasingly integrated. There are also strong investments in health, education, and institutions to enhance human and social capital. At the same time, the push for economic and social development is coupled with the exploitation of abundant fossil fuel resources and the adoption of resource and energy intensive lifestyles around the world. All these factors lead to rapid growth of the global economy, while global population peaks and declines in the 21st century. Local environmental problems like air pollution are successfully managed. There is faith in the ability to effectively manage social and ecological systems, including by geo-engineering if necessary.*

4. Demographic and Economic Drivers

The second step in developing the SSPs comprised the translation of the qualitative narratives into quantitative projections for the main socioeconomic drivers of the SSPs: population, education, urbanization, and economic development. These projections comprise the basic elements of the SSPs and were constructed at the country level. Aggregated results for the world are shown in Figure 2.

The SSP population projections (KC and Lutz, 2016) use a multi-dimensional demographic model to project national populations based on alternative assumptions on future fertility, mortality, migration and educational transitions. The projections are designed to be consistent with the five SSP storylines. They are cross-classified by age and gender as well as the level of education - with assumptions for female education strongly influencing fertility and hence population growth. The alternative fertility, mortality, and migration assumptions are derived partly from the storylines, reflecting also different educational compositions of the population. The outcomes in terms of total global population sizes of the SSPs cover a wide range. Consistent with the narratives, population is lowest in the SSP1 and SSP5 reaching about 7 billion people by 2100 and the highest in SSP3 reaching 12.6 billion in 2100. The middle of the road scenario (SSP2) depicts a population peaking at 9.4 billion (Figure 2). Compared to the SRES scenarios (Nakicenovic and Swart, 2000), i.e., the previous set of socioeconomic community scenarios, the new set covers a lower range. This is primarily due to the decline of fertility rates in emerging economies over the last two decades as well as the recent expansion of education among young women in least developed countries. Outcomes in terms of educational composition, which has important implications for economic growth and for vulnerability to climate change impacts, also vary widely across SSPs. In SSP1 and SSP5 composition improves dramatically, with the global average education level in 2050 reaching about the current level in Europe. SSP2 also shows substantial increases in educational composition, while in SSP3 and SSP4 increases are small and the global average education level even declines somewhat late in the century.

Similarly, the quantification of the urbanization trends follow the storylines (Jiang and O'Neill, 2016). The projections show that the world continues to urbanize across all SSPs, but rates of urbanization differ widely across them, with urbanization reaching between 60% (SSP3), 80% (SSP2), and 92% (SSP1, SSP4, SSP5) by the end of century (Figure 2). This range is much wider compared to earlier projections (Grübler et al., 2007). The middle of the road SSP2 projection is close to the UN median projection (UN, 2014). In SSP3, urbanization is constrained by slow economic growth, limited mobility across regions and poor urban planning that makes cities unattractive destinations. By contrast, urbanization is assumed to be rapid in both SSP1 and SSP5, which are associated with high income growth. Note, however, that in SSP1 urbanization is desired given the high efficiency that compact urban areas may achieve, while in SSP5 cities become attractive destinations due to other reasons, such as rapid technological change that allows for large-scale engineering projects to develop desirable housing.

There are three sets of economic (GDP) projections for each SSP (Crespo Cuaresma, 2016; Dellink et al., 2016; Leimbach et al., 2016). They were developed together with the demographic projections, in order to maintain consistency in assumptions with education and ageing. The three economic projections differ, however, in terms of their focus on different drivers of economic development (technological progress, efficiency improvements in energy use, income convergence dynamics or human capital accumulation). We employ Dellink et al. (2016) as the marker scenario for all SSPs to ensure consistency. The overall range of the SSPs is comparable to the range of earlier GDP projections in the literature (Figure 2). The highest SSP GDP projection (SSP5) depicts a very rapid development and convergence among countries with long-term global average income levels approaching almost 140,000 US$2005 per year in 2100. By contrast, the lowest projection (SSP3) depicts a development failure with strong fragmentation, leading to slow growth or long-term stagnation in most countries of the world. In the SSP3 world average income stays thus around 20,000 US$2005 per year in 2100 – this income level is broadly representative of the lowest long-term economic projections in the literature. In all scenarios, economic growth is projected to slow down over time, with average growth rates in the second half of the century roughly half of those in the first half. This slow-down is most marked in middle income countries. Note that all GDP projections were performed using international dollar in purchasing power parity (PPP) rates. An international dollar would buy in the cited country a comparable amount of goods and services a U.S. dollar would buy in the United States.

The SSP GDP projections also depict major differences in terms of cross-national inequality. Consistent with the narratives, SSP4 is characterized by the highest levels of inequality, representing a trend-reversal of the recent years (see the Gini index shown in panel D of Figure 2). Due to high fragmentation of the world, inequality also remains relatively high in SSP3 (compared to the other SSPs). The most equitable developments are depicted by SSP1 and SSP5, both featuring a rapid catch-up of the currently poor countries in the world.

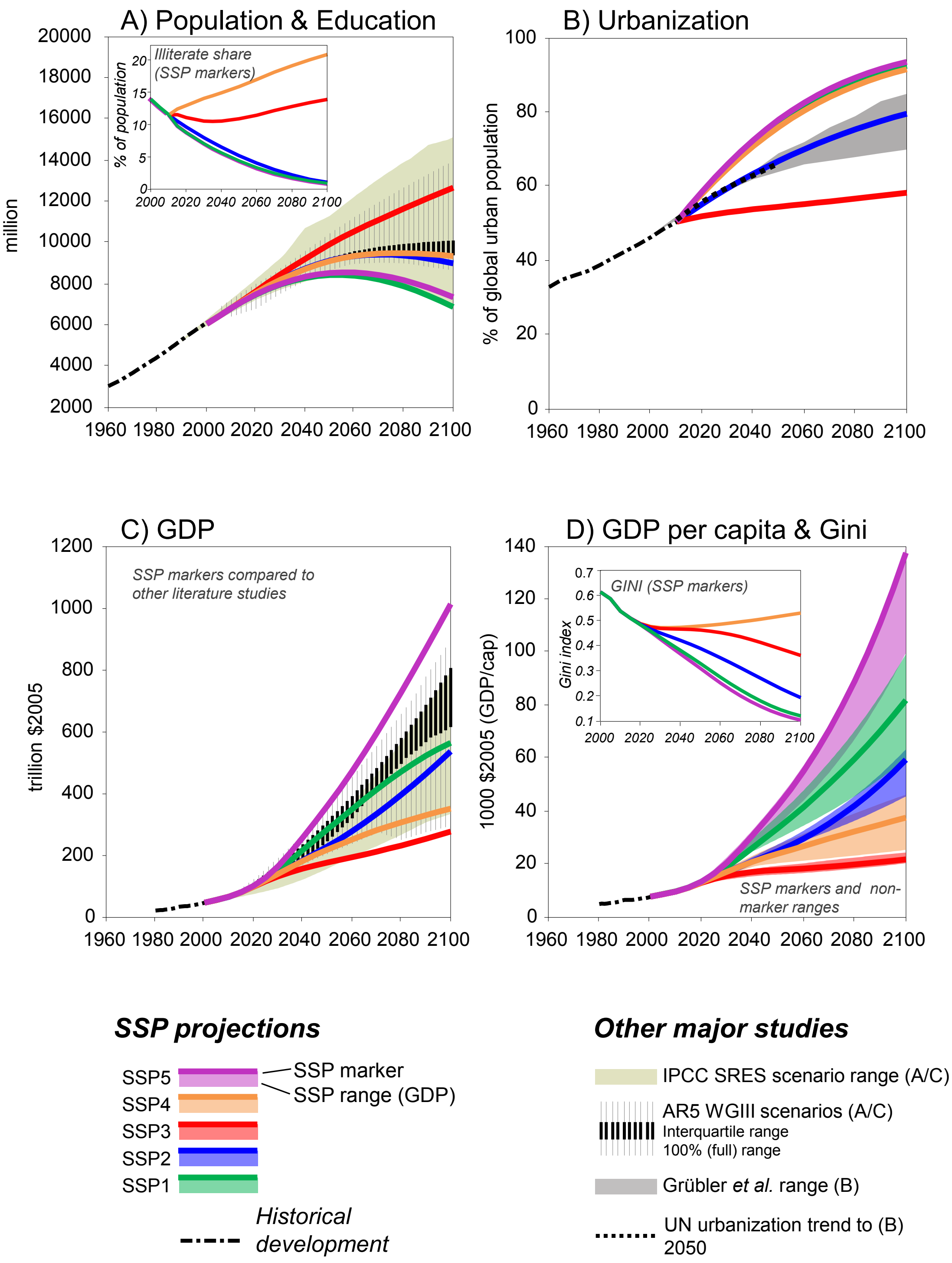

Figure 2: Development of global population and education (A), urbanization (B), GDP (C), and GDP per capita and the Gini index (D). The inset in panel A gives the share of people without education at age of >14 years, and the inset in panel D denotes the development of the global (cross-national) Gini index. The SSPs are compared to ranges from other major studies in the literature, such as the IPCC AR5 (Clarke et al., 2014); SRES (Nakicenovic and Swart, 2000), UN, and Grübler et al. (2007). The colored areas for GDP (panel D) denote the range of alternative SSP GDP projections presented in this Special Issue (Dellink et al. (2016), Crespo Cuaresma (2016), Leimbach et al. (2016)).

5. SSP baseline scenarios

5.1 Energy system

The SSP baseline scenarios describe alternative path-dependent evolutions of the energy system consistent with the SSP narratives and the associated challenges for mitigation and adaptation. Overall, the SSPs depict vastly different energy futures, featuring a wide range of possible energy demand developments and energy supply structures (Figure 3). These differences emerge due to a combination of assumptions with respect to the main drivers of the energy system, including technological change, economic growth, emergence of new energy services, energy intensity of services, and assumptions with respect to costs and availability of future fossil fuel resources and their alternatives (see Appendix A of the Supplementary Material and Bauer et al. (submitted) for further details).

The scale and structure of the future energy supply systems in the SSP scenarios are critical determinants of the challenges for mitigation and adaptation. Two of the SSP baseline scenarios (SSP3 and SSP5) have a heavy reliance on fossil fuels with an increasing contribution of coal to the energy mix (Figure 3: panel A and B). In these two SSPs, the challenges for mitigation are thus high. By contrast, SSP1 and SSP4 depict worlds with low challenges to mitigation, and consequently increasing shares of renewables and other low-carbon energy carriers. The “middle of the road” narrative of SSP2 leads to a balanced energy development compared to the other SSPs, featuring a continuation of the current fossil-fuel dominated energy mix with intermediate challenges for both mitigation and adaptation. These characteristics are also shown by the “SSP triangle” in Figure 3. The corners of the triangle depict hypothetical situations where the energy system would rely either fully on coal, “oil & gas” or “renewables and nuclear”. In this energy triangle, baseline scenarios for SSP3 and SSP5 are moving with time closer to the left corner dominated by coal, while SSP1 and SSP4 scenarios are developing toward the renewable and nuclear corner. The SSP2 scenario stays in the middle of the triangle.

The SSP baselines also span a wide range in terms of energy demand (Figure 3: Panel C), which is another major factor influencing the future challenges to mitigation and adaptation. At the upper end of the range, the SSP5 scenario exhibits a more than tripling of energy demand over the course of the century (primarily driven by rapid economic growth). As a result, SSP5 is characterized by high challenges to mitigation. Challenges to mitigation are lowest in SSP1 and SSP4 (Figure 3: Panel C), and this is reflected in the scale of energy demand in these scenarios. Demand is particularly low in the SSP1 scenarios peaking around 2060 and declining thereafter due to successful implementation of energy efficiency measures and behavioral changes. This leads to a global decoupling of energy demand from economic growth. Consistent with its intermediate mitigation challenges, final energy demand roughly doubles in the SSP2 scenario in the long term (2100) depicting a middle of the road pathway. Overall, the range of energy demand projections associated with the SSPs is broadly representative of the literature (covering about the 90th percentile range of the scenarios assessed in the IPCC AR5 (Clarke et al., 2014)).

Last but not least, the SSPs provide very different interpretations for energy access and poverty, which is an important indicator of the challenge to adaptation across the SSPs. The SSP3 and SSP4 baseline scenarios, for example, depict a failure of current policies for energy access, leading to continued and increased use of biomass in the households of developing countries (as defined today). By contrast, the use of coal and traditional biomass in households is reduced significantly in the other three baseline scenarios, which all portray comparatively more equitable worlds and thus also lower challenges for adaptation.

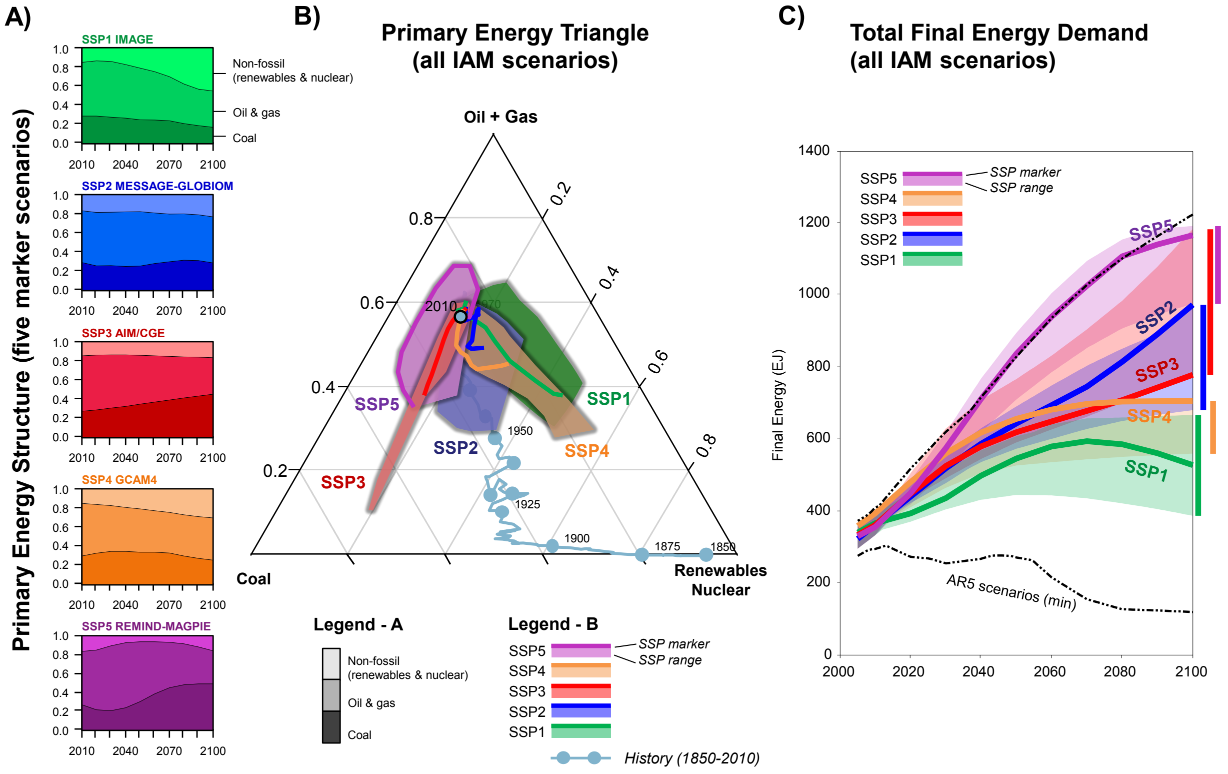

Figure 3: Primary energy structure (Panel A + B) and final energy demand (Panel C) of the SSP marker scenarios and corresponding ranges.

5.2 Land-use change

While there is a relatively long tradition of modeling comparisons in the area of energy-economic modeling (Clarke et al., 2009; Clarke et al., 2014; Edenhofer et al., 2010; Kriegler et al., 2015; Kriegler et al., 2014b; Riahi et al., 2015; Tavoni et al., 2015), there are fewer examples of systematic cross-model comparisons of land-use scenarios. Notable exceptions include (Nelson et al., 2014; Popp et al., 2014; Schmitz et al., 2014; Smith et al., 2010; Von Lampe et al., 2014). In this context, the SSPs are the first joint community effort in developing land-use scenarios based on common narratives as well as a harmonized set of drivers.

All SSP scenarios depict land-use changes in response to agricultural and industrial demands, such as food, timber, but also bioenergy. The nature and direction of these changes are, however, fundamentally different across the SSPs. They reflect land-use specific storylines that have been developed based on the SSP narratives (Popp et al., submitted) and which have guided assumptions on regulations, demand, productivity, environmental impacts, trade and the degree of globalization of future agricultural and forestry markets.

The land-use change components of the SSP baseline scenarios cover a broad range of possible futures. For example, the scenarios show that in the future total cultivated land can expand or contract by hundreds of millionsmillions of hectares over this century (Figure 4). Massive growth of population, relatively low agricultural productivity, and little emphasis on environmental protection makes SSP3 a scenario with comparatively large pressure on the global land-use system. The resulting land-use pattern is one with large-scale losses of forests and other natural lands due to an expansion of cropland and pasture land (Figure 4). In comparison, the SSP1 scenario features a sustainable land transformation with comparatively little pressure on land resources due to low population projections, healthy diets with limited food waste, and high agricultural productivity. Consistent with its narrative, this scenario depicts a reversal of historical trends, including a gradual, global-scale, and pervasive expansion of forests and other natural lands. All other SSP scenarios feature modest changes in land-use with some expansion of overall cultivated lands (Figure 4).

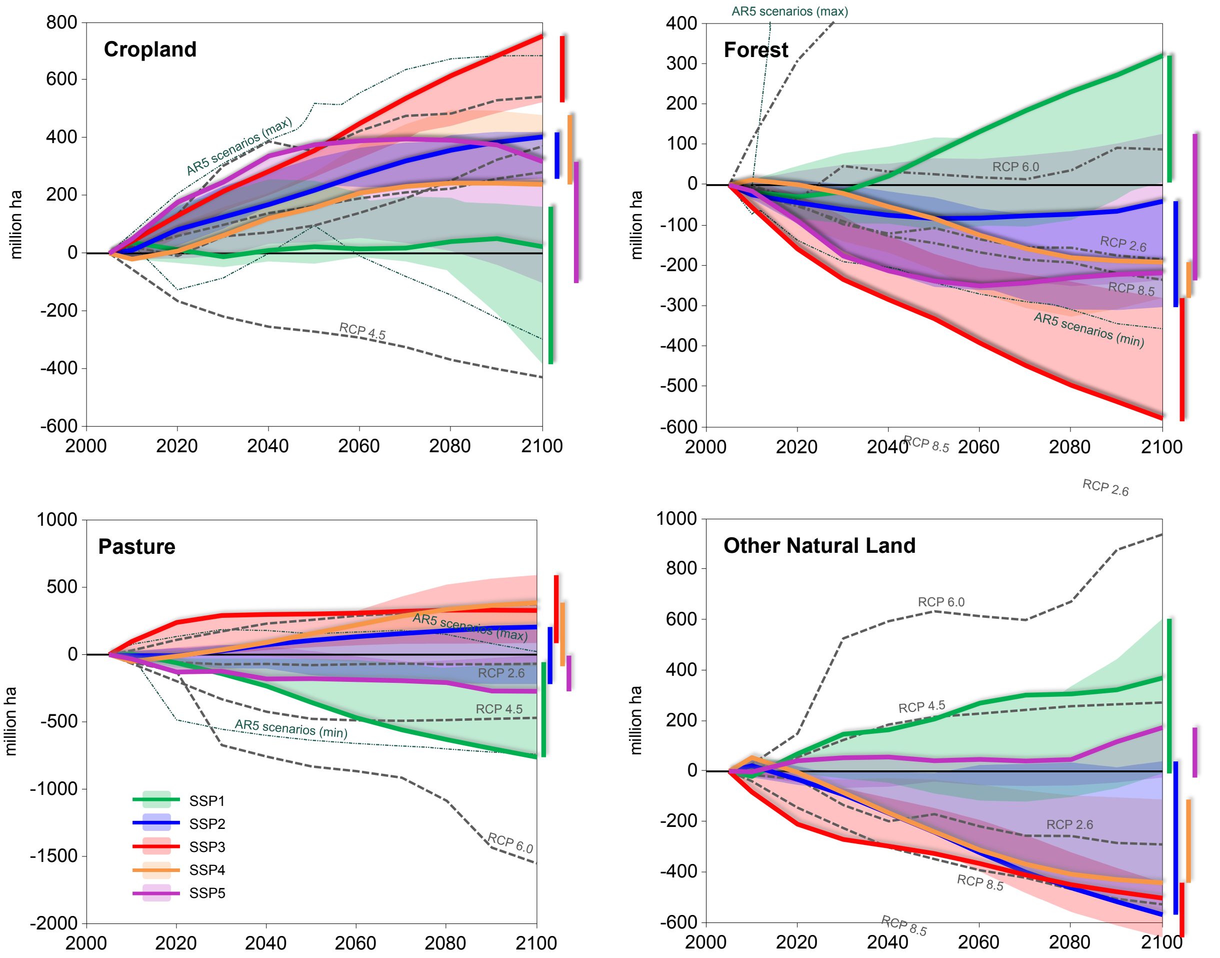

Figure 4: Changes in cropland, forest, pasture and other natural land for the SSP marker baseline scenarios (thick lines) and ranges of other non-marker scenarios (colored areas). Changes are shown relative to the base year of 2010 = 0. In addition to the SSP baseline scenarios also the development of the RCPs (van Vuuren et al, 2011) and the range of the IPCC AR5 scenarios are shown (Clarke et al, 2014). Note that cropland includes energy crops. Other natural land includes all land-categories beyond forests, pasture, cropland, and build-up areas (the latter category is comparatively small and has not been quantified by all models).

5.3 Baseline emissions and climate change

The pathways for the energy and land-use systems in the SSP scenarios translate into a wide range of GHG and pollutant emissions, broadly representative of the baseline range of the literature (Figure 5).

This is particularly the case for CO_2 emissions, which are strongly correlated with the future challenges for mitigation. The higher dependence on fossil fuels in the SSP3 and SSP5 baselines result in higher CO_2 emissions and a higher mitigation challenge. Similarly, comparatively low fossil fuel dependence and increased deployment of non-fossil energy sources (SSP1 and SSP4) results in lower CO_2 emissions and lower mitigation challenges (Figure 5). The SSP2 baseline depicts an intermediate emissions pathway compared to the other baselines, featuring a doubling of CO_2 emissions over the course of the century.

CH_4 is the second largest contributor to global warming (after CO_2). Current global emissions are dominated by non-energy sources like livestock, manure management, rice cultivation and enteric fermentation. To a lesser extent energy-related sources, including the production and transport of coal, natural gas, and oil, contribute to the emissions. Population growth and food demand is a strong driver of future CH_4 emissions across the SSPs. It is thus not surprising that CH_4 emissions are highest in the SSP3 baseline and lowest in SSP1. The combination of different energy and non-energy drivers leads in all other SSPs to intermediate levels of CH_4 emissions in the long term. Perhaps noteworthy is the rapid increase of CH_4 emissions in the SSP5 baseline in the near term, which is primarily due to the massive expansion of the fossil fuel infrastructure, particularly for the extraction and distribution of natural gas.

Important sources of N_2O emissions today include agricultural soil, animal manure, sewage, industry, automobiles and biomass burning. Agricultural soils and fertilization are the by far largest contributors of N_2O emissions, and remain so across all the SSPs. Emissions are highest in the SSP3 and SSP4 baselines due to high population and/or fertilizer use. N_2O emissions are lowest in SSP1, featuring sustainable agricultural practices and low population assumptions.

In summary, we find that total CO2 and CO2-eq. greenhouse gas emissions and the resulting radiative forcing correlate well with the challenges to mitigation across the SSPs. The results show at the same time, however, that plausible and internally consistent scenarios will not follow strictly the same ranking across all emissions categories (or across all SSP characteristics). It's thus important to note that the aggregated challenge for mitigation and adaptation is not only determined by the baseline but also the climate policy assumptions. The latter critically influence the effectiveness of climate policies, which are introduced on top of the baselines (see next section).

An important feature of the SSPs is that they cover a much wider range for air pollutant emissions than the RCPs (Rao et al., submitted). This is so since all the RCPs included similar assumptions about future air pollution legislation, assuming that the stringency of respective emissions standards would increase with raising affluence. It was not intended that the RCPs cover the full range of possible air pollutant emissions. In contrast, the SSPs are based on distinctly different air pollution storylines consistent with the overall SSP narratives. Particularly the upper bound projection of SSP3 features a world with slow introduction of air pollution legislation as well as implementation failures, leading to much higher air pollution emissions levels than in any of the RCPs (see Figure 5). For further details of the air pollution dimension of the SSPs, see Rao et al (submitted) in this special issue.

The resulting radiative forcing of the climate system is shown in the last panel of Figure 5. The SSP baselines cover a wide range between about 5.0 to 8.7 W/m^2 by 2100. Perhaps most importantly, we find that only one single SSP baseline scenario of the full set –SSP5– reaches radiative forcing levels as high as the one from RCP8.5. This is consistent across all IAM models that attempted to run the SSPs. As the SSPs systematically cover plausible combinations of the primary drivers of emissions, this finding suggests that 8.5 W/m^2 can only emerge under a relatively narrow range of circumstances. In contrast, an intermediate baseline (SSP2) only produces a forcing signal of about 6.5 W/m^2 (range 6.5 to 7.3 W/m^2). The lack of other SSP scenarios with climate forcing of 8.5 W/m^2 or above has important implications for impact studies, since SSP5 is characterized by low vulnerability and low challenges to adaptation. In order to add a high-end counterfactual for impacts to the current set of SSPs, it might be useful to develop a variant of an SSP that would combine high vulnerability with high climate forcing. This could be achieved for example by adding an alternative SSP3 interpretation with higher economic growth, to test whether such scenarios might lead to higher emissions consistent with RCP8.5 (see e.g., Ren et al., (2015)). The current SSP3 marker scenario leads to a radiative forcing of 7.2 W/m^2 (range 6.7 to 8.0 W/m^2).

The SSP1 baseline scenarios show the lowest climate signal of about 5 W/m^2 (range of 5.0 to 5.8 W/m^2). In order to reach radiative forcing levels below 5 W/m^2 it is thus necessary to introduce climate change mitigation policies, which are discussed in the next section.

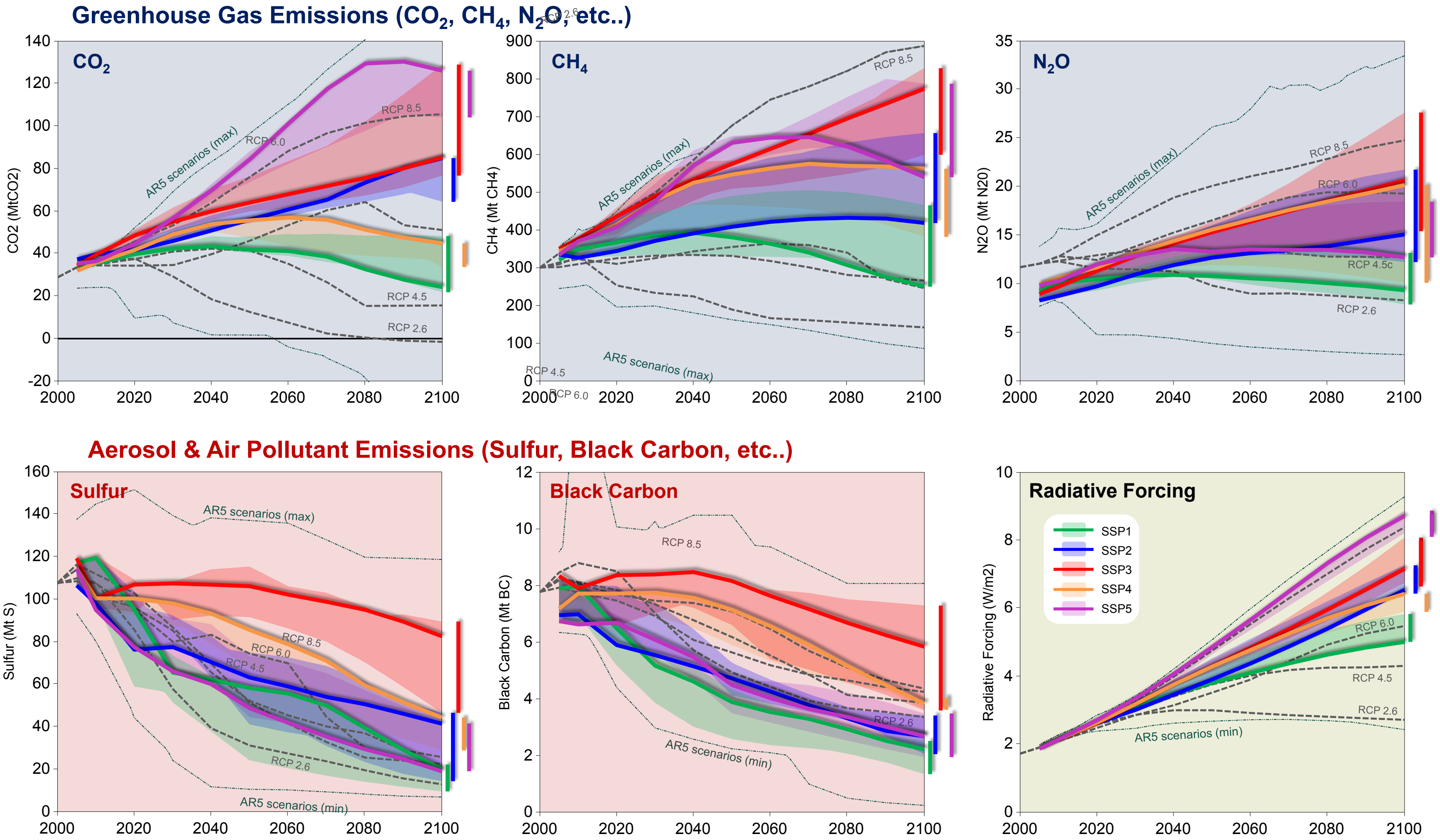

Figure 5: Global emissions and global average change in radiative forcing. SSP baseline marker scenarios (and ranges of SSP non-marker baseline scenarios) are compared to the RCPs (van Vuuren et al, 2011) and the full range of the IPCC AR5 scenarios (Clarke et al, 2014).

6. SSP mitigation scenarios

This section provides an overview of the SSP mitigation scenarios. Further details on the baseline and mitigation scenarios for individual SSPs can be found in this special issue in the five SSP marker scenario papers (Calvin et al., submitted; Fricko et al., submitted; Fujimori et al., submitted; Kriegler et al., submitted; van Vuuren et al., submitted) and two cross-cut papers on the SSP energy (Bauer et al., submitted) and land-use transitions (Popp et al., submitted).

6.1 Shared Climate Policy Assumptions

Mitigation costs and attainability of climate targets depend strongly on the design and effectiveness of future mitigation policies. Likewise, adaptation costs and the ability to buffer climate impacts depend on the scope and effectiveness of adaptation measures. These policies may differ greatly across the SSPs, and need to be consistent with the overall characteristic of the different narratives. Based on concepts from Kriegler et al. (2014a), we thus develop so-called shared climate policy assumptions (SPAs) for the implementation of the SSP mitigation scenarios. The mitigation SPAs describe in a generic way the most important characteristics of future mitigation policies, consistent with the overall SSP narrative as well as the SSP baseline scenario developments. More specifically, the mitigation SPAs describe critical issues for mitigation, such as the level of international cooperation (particularly in the short to medium term) and the stringency of the mitigation effort over time. The mitigation SPAs also define the coverage of different economic sectors, and particularly the land-use sector, which traditionally has been a challenging sector for mitigation in many countries.

The definitions of the mitigation SPAs were derived by considering three main guiding principles: 1) The SPA/SSP combination is selected with the primary aim to reinforce the challenges for mitigation described by the relative position of each SSP in the challenges space; 2) the expected overall impact of the mitigation policy is selected to be consistent with the SSP storyline (for example, specific sectors or policy measures are less effective in some of the storylines compared to others); and 3) the mitigation SPAs are defined in broader terms only, providing the modeling teams a high degree of flexibility to choose between different possible policy instruments for the implementation of the SPAs into the IA models. The main assumptions of the mitigation SPAs are summarized in Table 3.

Consistent with the storyline of strong fragmentation, poverty, and low capacity for mitigation, SSP3 assumes an SPA with late accession of developing countries, as well as low effectiveness of the climate policies in the agricultural and land sector (driven by rural poverty and low agricultural productivity). In comparison, the emphasis of SSP1 on sustainability results in this world in a highly effective and collaborative policy environment with globally comprehensive mitigation actions. Other SSPs combine different characteristics of the SPAs as shown in Table 3.

The above SPAs and the different underlying socioeconomic and technological assumptions lead to distinctly different near-term (2030) GHG emissions developments across the SSP scenarios. In the context of the current international agreements, the marker scenarios of SSP1 and SSP4 depict low mitigation challenges and thus describe developments that allow a further strengthening of near-term mitigation measures beyond those described by the intended nationally determined contributions (INDCs) under the Paris agreement (UNFCCC, 2015). On the other hand, the INDCs are not fully achieved in the SSP marker scenarios with high challenges to mitigation (SSP3 and SSP5). Near-term emissions of the middle-of-the-road SSP2 marker scenario are broadly consistent with the INDCs (see Figure S5 in the Supplementary Material).

Table 3: Summary of Shared Climate Policy Assumptions (SPAs) for mitigation. All SPAs foresee a period with moderate and regionally fragmented action until 2020, but differ in the development of mitigation policies thereafter (see Section 6 and Appendix B of the Supplementary Material for further details and definitions).

Policy stringency in the near term and the timing of regional participation	Coverage of land use emissions
SSP1, SSP4 Early accession with global collaboration as of 2020	***SSP1, SSP5*** Effective coverage (at the level of emissions control in the energy and industrial sectors)
SSP2, SSP5 Some delays in establishing global action with regions transitioning to global cooperation between 2020-2040	***SSP2, SSP4*** Intermediately effective coverage (limited REDD*, but effective coverage of agricultural emissions)
SSP3 Late accession – higher income regions join global regime between 2020-2040, while lower income regions follow between 2030-2050	***SSP3*** Very limited coverage (implementation failures and high transaction costs)

*REDD: Reducing Emissions from Deforestation and forest Degradation

Finally, it is important to note that while the adaptation dimension have not been quantified in the scenarios (see also Section 7 on Conclusions), the SSPs differ greatly with respect to the challenges to adaptation as well as the associated effectiveness of possible adaptation policies (O'Neill et al., 2014). For example in SSP1, the capacity to adapt to climate change is high given the well-educated, rich population, the high degree of good governance and the high development of technologies. In addition, also the intact ecosystem services contribute to the adaptive capacity. In SSP3, on the other hand the capacity to adapt to climate change is relative low, given the large, poor population, the lack of cooperation and low of technology development. In SSP4, the capacity to adapt to climate change is relatively low for most of the population in each region, given the unequal distribution of resources. And finally in SSP5, the capacity to adapt to climate change is high given a highly educated and rich population as well as the high level of technology development. SSP2 depicts intermediate adaptation capacity compared to the other SSP scenarios. In future research, the SPAs will need to be extended by an adaptation dimension in order to integrate climate impacts and adaptation into the scenario analysis.

6.2 Mitigation strategies

The reduction of GHG emissions can be achieved through a wide portfolio of measures in the energy, industry and land-use sectors, the main sources of emissions and thus global warming (Clarke et al., 2014). In the energy sector, the IA models employ a combination of measures to introduce structural changes through, e.g., replacement of carbon-intensive fossil fuels by cleaner alternatives (such as a switch from coal to natural gas, or the upscaling of renewable energy) and demand-side measures geared toward energy conservation and efficiency improvements (Bauer et al., submitted; Calvin et al., submitted; Fricko et al., submitted; Fujimori et al., submitted; Kriegler et al., submitted; Popp et al., submitted; van Vuuren et al., submitted). The latter include also the electrification of energy demand. In addition to structural changes, carbon capture and storage (CCS) can be employed to reduce the carbon-intensity of fossil fuels or can even be combined with bioenergy conversion technologies for the delivery of energy services with potentially net negative emissions. Primary measures in the agricultural sector comprise reduction of CH_4 and N_2O emissions from various sources (livestock, rice, fertilizers) and dedicated measures to reduce deforestation and/or encourage afforestation and reforestation activities.

The mitigation effort required to achieve a specific climate forcing target depends greatly on the SSP baseline scenario. Autonomous improvements in some baselines, e.g., in terms of carbon intensity and/or energy intensity (see SSP1, Figure 6) can greatly reduce the residual effort needed to attain long-term mitigation targets. By the same token, however, the lack of structural changes in the baseline

(SSP5) or relatively high levels of energy intensity (SSP3) inevitably translate into the need for comparatively higher mitigation efforts.

This path-dependency of mitigation is illustrated in Figure 6. It is shown how the introduction of climate policies leads to concurrent improvements of both the energy and the carbon intensity of the economy. At the same time, the figure also clearly illustrates that the required relative “movement” of the mitigation scenarios (i.e., the combination of measures for carbon and energy intensity) are strongly dependent on the position of the baseline (in Figure 6). For example, the carbon and energy intensity improvement rates of the SSP3 baseline are slower even than the recent historical rate (1971-2010). Hence, the distance of the SSP3 baseline to reach stringent climate targets - such as limiting temperature change to below 2°C (see Figure 6) - is much larger than, for example, the distance for the SSP1 baseline scenario. As a matter of fact reaching the lowest target of 2.6 W/m^2 from an SSP3 baseline was found infeasible across all IAM models (Figure 8).

Achieving stringent climate targets requires a fundamental transformation of the energy system, including the rapid upscaling of low-carbon energy (renewables, nuclear and CCS) (Figure 7). Independently of the SSP, we find that for reaching 3.4 W/m^2 about half of the energy system (range: 30-60%) will need to be supplied by low-carbon options in 2050, while for 2.6 W/m^2 these options need to supply even about 60% (range: 40-70%) of the global energy demand in 2050. This corresponds to an increase of low-carbon energy share by more than a factor of three compared to today (in 2010 the low-carbon share was 17%). In comparison, none of the SSP baselines show structural changes that are comparable to the requirements of 3.4 or 2.6 W/m^2. Only the SSP1 baseline depicts noteworthy increases reaching a contribution of about 30% of low-carbon energy by 2050 (most SSP3 and SSP5 baseline scenarios are showing even a decline of the share of low-carbon energy by 2050 in absence of additional climate policies).

CCS plays an important role in many of the mitigation scenarios even though its deployment is subject to large uncertainties (Figure 7, right panel). Therefore, depending on the SSP interpretation of different models, the contribution of CCS ranges from zero to almost 1900 $GtCO_2$. As shown by the marker SSP scenarios, fossil-intensive baselines, such as SSP3 and SSP5, show generally higher needs for CCS compared to less fossil-intensive baselines. Consistent with the narrative of sustainability, the contribution of CCS is lowest in the SSP1 marker scenario (Figure 7).

Important mitigation options outside the energy sector include reduced deforestation, the expansion of forest land cover (afforestation and/or reforestation) as well as the reduction of the greenhouse gas intensity of agriculture (Figure 7, middle panel). While uncertainties for land-based mitigation options are generally among the largest, we nevertheless find that the mitigation strategies of the marker SSP scenarios reflect well the underlying narratives (see also Popp et al. (submitted)). The expansion of forest land cover is an important factor in the mitigation scenarios of the SSP1 marker (Figure 7), followed by SSP2 and SSP4. The IAM model of the SSP5 marker does not consider mitigation-induced afforestation, implying that CO2 emissions from land use are phased out by reducing and eventually eliminating deforestation in all SSP5 mitigation cases, but no expansion of forest area and associated CO2 withdrawal occurs. Finally, the SSP3 marker scenario shows a different dynamic due to high pressure on land. Already the SSP3 baseline is characterized by shrinking forest areas. This trend is further accelerated in the mitigation scenarios due to the expansion of bioenergy. SSP3 depicts thus a future world with massive challenges for land-based mitigation, where GHG policies add further pressure on the land system, resulting in competition for scarce resources between food and bioenergy production.

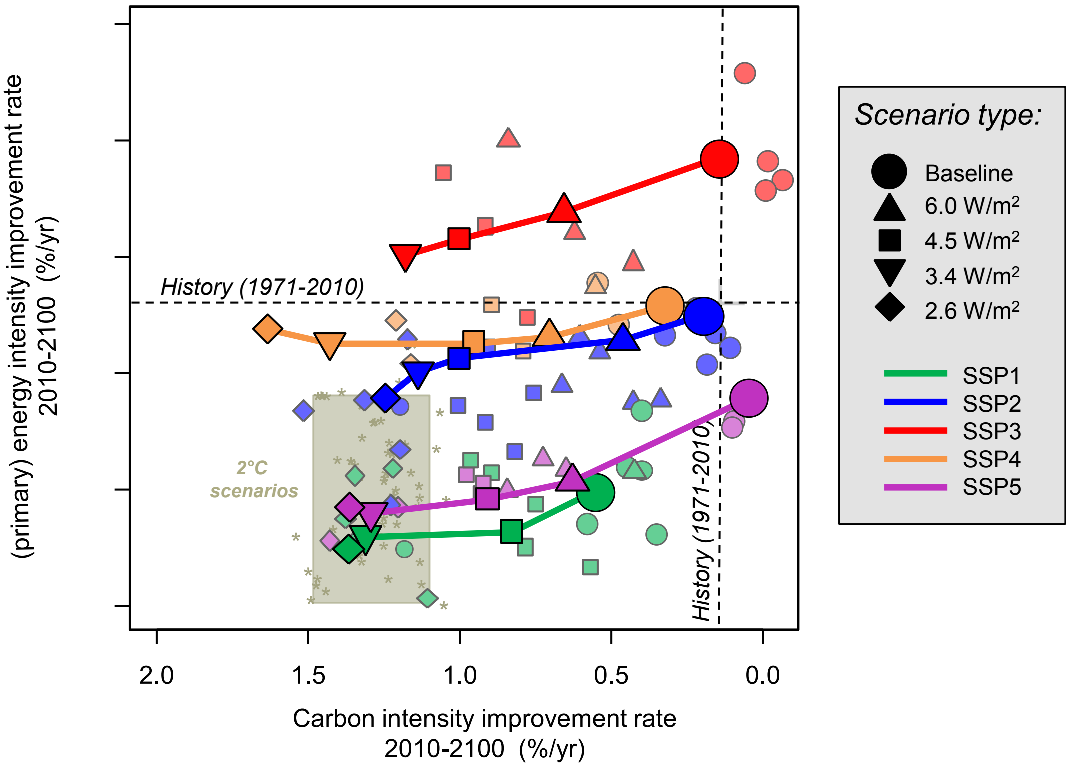

Figure 6: Annual long-term improvement rates of energy intensity (final energy/GDP) and carbon intensity (CO_2/final energy). Development in the SSP baseline and mitigation scenarios are compared to scenarios consistent with a likely chance to stay below 2°C from the IPCC AR5 (shaded area). Large icons and colored lines denote the SSP marker and associated mitigation scenarios. Smaller icons denote non-marker IAM interpretations of the SSPs.

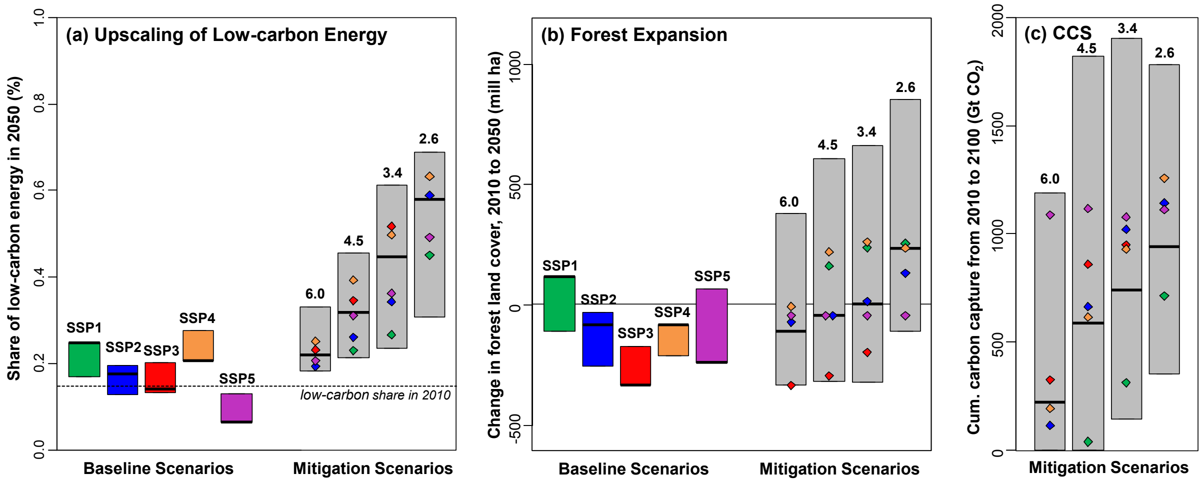

Figure 7: Major mitigation options in the energy and land-use sector: (a) upscaling of low carbon energy by 2050, (b) expansion of forest land-cover by 2050, and (c) contribution of cumulative CCS over the course of the century. The range of the SSP baseline scenarios are shown as colored bars. Horizontal black lines within the colored bars give the relative position of the SSP baseline marker scenarios. The full range of results for the mitigation scenarios are shown as grey bars. Colored symbols within the grey bars denote the relative position of the marker mitigation scenarios and the horizontal black lines

within the grey bars denote the median across the mitigation scenarios. Note that the number of scenarios differs across the different baseline and mitigation bars.

6.3 Mitigation costs and attainability

The comprehensive mitigation experiments enable us to fill the “matrix” of the scenario framework with mitigation costs from different SSP scenarios (see Figure 8 and Section 1 of the Supplementary Material). For each mitigation target (i.e., 2100 forcing level) and each SSP we have computed costs for the SSP marker model as well as associated ranges of other non-marker IAMs.

Mitigation costs are shown in terms of the net present value (NPV) of the average global carbon price over the course of the century. The price is calculated as the weighted average across regions using a discount rate of 5%. We select this cost metric since not all models are able to compute full macroeconomic costs in terms of GDP or consumption losses. Results for those models that report these cost metrics can be found in Section 1 of the Supplementary Material.

Our results are consistent with other major comparison studies (Clarke et al., 2014; Kriegler et al., 2015; Riahi et al., 2015) which suggest that carbon prices for achieving specific climate targets may vary significantly across models and scenarios. For example, the average carbon prices for the target of 2.6 W/m^2 differ in our analysis by about a factor of three across the marker scenarios from about 9 $\$/tCO_2$ in the SSP1 marker to about 25 $\$/tCO_2$ in the SSP5 marker. Our highest estimate across all scenarios (>100 $\$/tCO_2$) is representative of about the 90th percentile of comparable scenarios assessed by the IPCC AR5 (category I scenarios, see Clarke et al, 2014), while the lowest in our scenario set is lower than comparable estimates from AR5. In other words, we are able to cover with our limited set of models a large part of the overall literature range. The average carbon price in the middle-of-the-road SSP2-2.6 W/m^2 scenario is about 10 $\$/tCO_2$ (range: 10-110 $\$/tCO_2$, Figure 8). The SSP2 marker costs are somewhat lower than the median cost estimate of the scenarios for similar targets assessed by the IPCC AR5 (30 $\$/tCO_2$). The wide range of costs is also an important indication that (consistent with our original objective), the scenarios cover a significant range with respect to the challenges for mitigation. Perhaps more importantly, we can consistently relate the differences in the mitigation costs to alternative assumptions on future socioeconomic, technological and political developments. This illustrates the importance of considering alternative SSPs and SPAs and their critical role in determining the future mitigation challenges.

Consistent with the narratives, mitigation costs and thus the challenge for mitigation is found lower in SSP1 & SSP4 relative to SSP3 & SSP5 (Figure 8). Perhaps most importantly, we find that not all targets are necessarily attainable from all SSPs. Specifically the 2.6 W/m^2 target was found by all models infeasible to reach from an SSP3 baseline, and the WITCH-GLOBIOM model found it infeasible to reach the target in SSP5 (all other models reached 2.6 W/m^2 from SSP5). The fact that IAMs could not find a solution for some of the 2.6 W/m^2 scenarios needs to be distinguished from the notion of infeasibility in the real world. As indicated by Riahi et al. (2015) model infeasibilities may occur for different reasons, such as lack of mitigation options to reach the specified climate target; binding constraints for the diffusion of technologies or extremely high price signals under which the modeling framework can no longer be solved. Thus, infeasibility in this case is an indication that under the specific socioeconomic and policy assumptions of the SSP3 scenario (and to a less extent also SSP5 scenario) the transformation cannot be achieved. It provides useful context for understanding technical or economic concerns. These concerns need to be strictly differentiated from the feasibility of the transformation in the real world, which hinges on a number of other factors, such as political and social concerns that might render feasible model solutions unattainable in the real world (Riahi et al., 2015). Infeasibility, in the case of SSP3, is thus rather an indication of *increased risk* that the required transformative changes may not be attainable due to technical or economic concerns.

In all other SSPs (Figure 8), IAMs found the 2.6 W/m^2 to be attainable, and it is possible that yet lower forcing levels might be attainable in some of these SSPs. As a matter of fact, some studies indicate that under certain conditions targets as low as 2.0 W/m2 might still be attainable during this century (Luderer et al., 2013; Rogelj et al., 2015; Rogelj et al., 2013a; Rogelj et al., 2013b). As a follow-up research activity to this special issue, the IAM teams are planning to use the SSP framework for a systematic exploration of the attainability of such low targets.

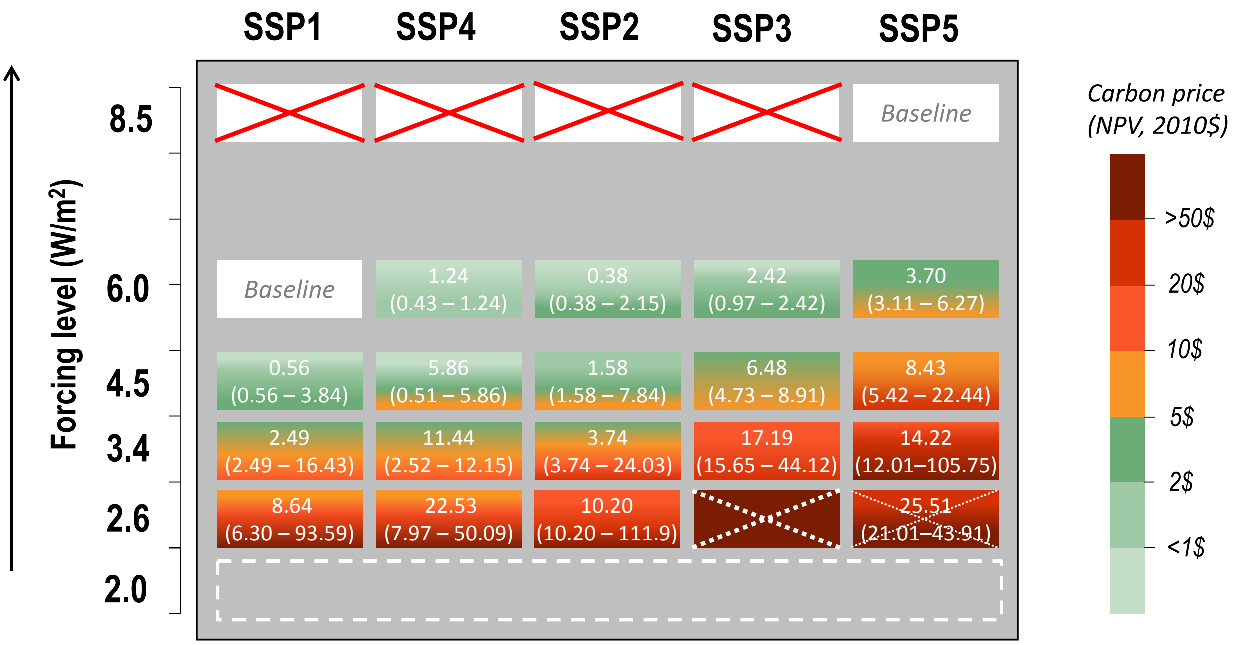

Figure 8: Carbon prices and the attainability of alternative forcing targets across the SSPs. The colors of the cells are indicative of the carbon price. The numbers in the boxes denote the carbon price of the marker scenarios with the full range of non-marker scenarios in parenthesis. White cells indicate the position of the respective baseline scenarios. Empty (crossed) cells could not be populated. Carbon prices are shown in terms of the net present value (NPV) of the average global carbon price from 2010 to 2100 using a discount rate of 5%. Mitigation costs for other metrics (GDP losses, consumption losses, and abatement costs) are provided as well in Section 1 of the Supplementary Material. Note that the SSP columns are ordered according to increasing mitigation challenges (low challenges (SSP1/SSP4), intermediate challenges (SSP2) and high mitigation challenges (SSP3/SSP5)).

7. Discussion and conclusions

We have shown how different SSP narratives can be translated into a set of assumptions for economic growth, population change, and urbanization, and how these projections can in turn be used by IAM models for the development of SSP baseline and mitigation scenarios. By doing so, this paper presented an overview of the main characteristics of five Shared Socioeconomic Pathways (SSPs) and related integrated assessment scenarios. These are provided to the community as one of the main building blocks of the "new scenario framework" (O'Neill et al, 2014, van Vuuren et al, 2014).

This overview paper is complemented by additional articles in this special issue. Together the papers provide a detailed discussion of the different dimensions of the SSPs with the aim to offer the community a set of common assumptions for alternative socioeconomic development pathways. These pathways can be combined with different climate policy assumptions (SPAs) and climate change projections (e.g., the RCPs) and thus facilitate the integrated analyses of impacts, vulnerability, adaptation and mitigation. The SSP scenarios presented here do not consider feedbacks due to climate change or associated impacts (with exception of the IMAGE scenarios which include the effect of fertilization on forest growth due to changing CO_2 concentrations). This makes these scenarios particularly relevant for subsequent impact studies, since it facilitates the superposition of physical climate changes on top of the SSP scenarios to derive consistent estimates of impacts (or adaptation). The narratives, quantitative drivers, and IAM scenarios serve the purpose of providing the IAV, IAM and climate modeling community with information that enables them to use the scenario framework for a new generation of climate research. This special issue should be seen thus as a starting point for new climate change assessments through the lens of the SSPs and the new scenario framework.

We find that while the SSPs and the associated scenarios were designed to represent different characteristics for the challenges to mitigation and adaptation, for many dimensions the resulting quantifications span a wide range broadly representative of the current literature. This is particularly the case for the SSP population and GDP projections as well as for the greenhouse gas emissions of the associated baseline scenarios. For some dimensions the SSPs go even beyond the historical ranges from the literature. This is specifically the case for urbanization where there has been little work in the past to explore the space of possibilities, and for air pollutant emissions. For the latter, the SSP scenarios span a considerably wider range compared to the RCPs, since the SSP scenarios explicitly consider alternative air pollution policy futures (in contrast to the RCPs, which were based on intermediate assumptions for air pollution legislation).

Using multiple models for the development of the economic projections and the SSP scenarios was important in order to understand the robustness of the results and to be able to explore structural model uncertainties in comparison to uncertainties conditional on the interpretation of different SSP narratives. The development of the SSPs and their associated scenarios involved multiple rounds of public and internal reviews and the selection of marker SSP scenarios. While the markers can be interpreted as representative of a specific SSP development, they are not meant to provide a central or median interpretation. For each SSP alternative outcomes are possible, and the different IAMs are used to project conditional uncertainties that might be attributed to model structure and/or the interpretation/implementation of the qualitative storylines. Thus, in order to capture these uncertainties it is generally recommended to use as many realizations of each SSP as possible.

By employing a systematic mitigation analysis across the SSPs, we have also conducted the first application of the scenario framework for the mitigation dimension. We find that mitigation costs depend critically on the SSPs and the associated socioeconomic and policy assumptions. While our study could not reduce the large uncertainties associated with mitigation costs (Clarke et al., 2014), the SSP mitigation experiments have nonetheless helped to illustrate the role of various sources of uncertainty, including the extent to which mitigation costs may depend on different models or different interpretations of storylines.

Another important finding from our assessment is that not all cells of the scenario matrix could be populated. On the high end, only SSP5 led to radiative forcing levels as high as RCP8.5, while at the low end it was not possible to attain radiative forcing levels of 2.6 W/m^2 in an SSP3 world. However, we cannot rule out the possibility that plausible combinations of assumptions could be identified that would enable the currently empty cells to be populated. For example, somewhat higher economic growth assumptions in a variant of SSP3 might lead to higher climate change (8.5 W/m^2; Ren et al., 2015). Such an SSP3 variant would be relevant since it would combine high climate change with high vulnerability. Similarly, the results of the SSPs with low challenges to mitigation, particularly SSP1, indicate that it might be possible to reach yet lower radiative forcing levels than those included in the current matrix. Hence, efforts in the IAM community have started to apply the SSP framework for the development of deep mitigation scenarios that could extend the scenario matrix at the low end.

The next steps of the community scenario process will comprise collaboration with the climate modeling teams of CMIP6 (Eyring et al., 2015) to assess the climate consequences of the SSPs. This work is organized as part of ScenarioMIP (O'Neill et al., 2016b). In addition, the modeling protocol that has been developed as part of this study (see Appendix A-C of the supplementary material) is made available to the IAM community in order to enable widespread participation of additional IAM modeling teams in quantifying the SSPs. Most importantly, the SSPs and associated scenarios aim to enable impacts, adaptation and vulnerability researchers to explore climate impacts and adaptation requirements under a range of different socio-economic developments and climate change projections. The plan is for an evolutionary expansion of the scenario framework matrix, so that a large body of literature based on comparable assumptions can emerge. Beyond the work on the global SSPs, important extensions are either planned or are under way (van Ruijven et al., 2014). These include extensions with respect to other sectors (e.g., www.isi-mip.org), specific regions (e.g., for the US (Absar and Preston, 2015) and for Europe (Alfieri et al., 2015)), or increased granularity and heterogeneity, for example, with respect to income distributions or spatially downscaled information on key socioeconomic drivers.

All results presented in this special issue are available on-line at the interactive SSP web-database hosted at IIASA: https://secure.iiasa.ac.at/web-apps/ene/SspDb/

References

Absar, S.M., Preston, B.L. (2015) Extending the Shared Socioeconomic Pathways for sub-national impacts, adaptation, and vulnerability studies. Global Environmental Change 33, 83-96.

Alfieri, L., Feyen, L., Dottori, F., Bianchi, A. (2015) Ensemble flood risk assessment in Europe under high end climate scenarios. Global Environmental Change 35, 199-212.

Bauer, N., Katherine Calvin, Johannes Emmerling, Oliver Fricko, Shinichiro Fujimori, Jérôme Hilaire, Jiyong Eom , Volker Krey, Elmar Kriegler, Ioanna Mouratiadou, Harmen Sytze de Boer, Maarten van den Berg, Samuel Carrara, Laurent Drouet, Jae Edmonds, David Gernat, Mathijs Harmsen, Petr Havlik, Nils Johnson, Page Kyle, Gunnar Luderer, Giacomo Marangoni, Toshihiko Masui, Jessica Strefler, Manfred Strubegger, Marshall Wise, Keywan Riahi, Vuuren, D.P.v. (submitted) Shared Socio-Economic Pathways of the Energy Sector – Quantifying the Narratives. Global Environ. Change.

Calvin, K., Ben Bond-Lamberty, Leon Clarke, James Edmonds, Jiyong Eom, Corinne Hartin, Sony Kim, Page Kyle, Robert Link, Richard Moss, Haewon McJeon, Pralit Patel, Steve Smith, Stephanie Waldhoff, Wise, M. (submitted) SSP4: A World of Inequality. Global Environ. Change.

Clarke, L., Edmonds, J., Krey, V., Richels, R., Rose, S., Tavoni, M. (2009) International climate policy architectures: Overview of the EMF 22 International Scenarios. Energy Economics 31, S64-S81.

Clarke, L., Jiang, K., Akimoto, K., Babiker, M., Blanford, G., Fisher Vanden, K., Hourcade, J., Krey, V., Kriegler, E., Löschel, A., McCollum, D., Paltsev, S., Rose, S., R. Shukla, P., Tavoni, M., van der Zwaan, B., van Vuuren, D.P., (2014) Assessing Transformation Pathways, in: Edenhofer, O., Pichs-Madruga, R., Sokona, Y., Farahani, E., Kadner, S., Seyboth, K., Adler, A., Baum, I., Brunner, S., Eickemeier, P., Kriemann, B., Savolainen, J., Schlömer, S., von Stechow, C., Zwickel, T., Minx, J.C. (Eds.), Climate Change 2014: Mitigation of Climate Change. Contribution of Working Group III to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change Cambridge University Press, Cambridge, United Kingdom.

Crespo Cuaresma, J. (2016) Income projections for climate change research: A framework based on human capital dynamics. Global Environ. Change.

Dellink, R., Chateau, J., Lanzi, E., Magné, B. (2016) Long-term economic growth projections in the Shared Socioeconomic Pathways. Global Environmental Change.

Ebi, K.L., Hallegatte, S., Kram, T., Arnell, N.W., Carter, T.R., Edmonds, J., Kriegler, E., Mathur, R., O'Neill, B.C., Riahi, K., Winkler, H., van Vuuren, D.P., Zwickel, T. (2014) A new scenario framework for climate change research: Background, process, and future directions. Climatic Change 122, 363-372.

Edenhofer, O., Knopf, B., Barker, T., Baumstark, L., Bellevrat, E., Chateau, B., Criqui, P., Isaac, M., Kitous, A., Kypreos, S., Leimbach, M., Lessmann, K., Magné, B., Scrieciu, Š., Turton, H., Van Vuuren, D.P. (2010) The economics of low stabilization: Model comparison of mitigation strategies and costs. Energy Journal 31, 11-48.

Eyring, V., Bony, S., Meehl, G.A., Senior, C., Stevens, B., Stouffer, R.J., Taylor, K.E. (2015) Overview of the Coupled Model Intercomparison Project Phase 6 (CMIP6) experimental design and organisation. Geosci. Model Dev. Discuss. 8, 10539-10583.

Field, C.B., Barros, V.R., Mastrandrea, M.D., Mach, K.J., Abdrabo, M.-K., Adger, N., Anokhin, Y., Anisimov, O., Arent, D., Barnett, J. (2014) Summary for policymakers. Climate change 2014: impacts, adaptation, and vulnerability. Part A: global and sectoral aspects. Contribution of Working Group II to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change, 1-32.

Fricko, O., Petr Havlik, Joeri Rogelj, Keywan Riahi, Zbigniew Klimont, Mykola Gusti, Nils Johnson, Peter Kolp, Manfred Strubegger, Hugo Valin, Markus Amann, Tatiana Ermolieva, Nicklas Forsell, Mario Herrero, Chris Heyes, Georg Kindermann, Volker Krey, David L. McCollum, Michael Obersteiner, Shonali Pachauri, Shilpa Rao, Erwin Schmid, Schoepp, W. (submitted) SSP2: a middle-of-the-road scenario for the 21st century. Global Environ. Change.

Fujimori, S., Tomoko Hasegawa, Toshihiko Masui, Kiyoshi Takahashi, Diego Silva Herran, Hancheng Dai, Yasuaki Hijioka, Kainuma, M. (submitted) AIM Implementation of Shared Socioeconomic Pathways. Global Environ. Change.

Grübler, A., O'Neill, B., Riahi, K., Chirkov, V., Goujon, A., Kolp, P., Prommer, I., Scherbov, S., Slentoe, E. (2007) Regional, national, and spatially explicit scenarios of demographic and economic change based on SRES. Technological Forecasting and Social Change 74, 980-1029.

IPCC (2013) Summary for Policymakers. In: Climate Change 2013: The Physical Science Basis. Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA.

Jiang, L., O'Neill, B.C. (2016) Global urbanization projections for the Shared Socioeconomic Pathways. Global Environmental Change.

KC, S., Lutz, W. (2016) The human core of the shared socioeconomic pathways: Population scenarios by age, sex and level of education for all countries to 2100. Global Environmental Change.

Kriegler, E., Edmonds, J., Hallegatte, S., Ebi, K.L., Kram, T., Riahi, K., Winkler, H., van Vuuren, D.P. (2014a) A new scenario framework for climate change research: The concept of shared climate policy assumptions. Climatic Change 122, 401-414.

Kriegler, E., Nico Bauer, Alexander Popp, Florian Humpenöder, Marian Leimbach, Jessica Strefler, Lavinia Baumstark, Benjamin Bodirsky, Jerome Hilaire, David Klein, Ioanna Mouratiadou, Isabelle Weindl, Christoph Bertram, Jan-Philipp Dietrich, Gunnar Luderer, Michaja Pehl, Robert Pietzcker, Franziska Piontek, Hermann Lotze-Campen, Anne Biewald, Markus Bonsch, Anastasis Giannousakis, Ulrich Kreidenweis, Christoph Müller, Susanne Rolinski, Jana Schwanitz, Stefanovic, M. (submitted) Fossil-fueled development (SSP5): an energy and resource intensive scenario for the 21st century. Global Environ. Change.

Kriegler, E., O'Neill, B.C., Hallegatte, S., Kram, T., Lempert, R.J., Moss, R.H., Wilbanks, T. (2012) The need for and use of socio-economic scenarios for climate change analysis: A new approach based on shared socio-economic pathways. Global Environmental Change 22, 807-822.

Kriegler, E., Riahi, K., Bauer, N., Schwanitz, V.J., Petermann, N., Bosetti, V., Marcucci, A., Otto, S., Paroussos, L., Rao, S., Arroyo Currás, T., Ashina, S., Bollen, J., Eom, J., Hamdi-Cherif, M., Longden, T., Kitous, A., Méjean, A., Sano, F., Schaeffer, M., Wada, K., Capros, P., P. van Vuuren, D., Edenhofer, O. (2015) Making or breaking climate targets: The AMPERE study on staged accession scenarios for climate policy. Technological Forecasting and Social Change 90, 24-44.

Kriegler, E., Weyant, J.P., Blanford, G.J., Krey, V., Clarke, L., Edmonds, J., Fawcett, A., Luderer, G., Riahi, K., Richels, R., Rose, S.K., Tavoni, M., van Vuuren, D.P. (2014b) The role of technology for achieving climate policy objectives: Overview of the EMF 27 study on global technology and climate policy strategies. Climatic Change 123, 353-367.

Leimbach, M., Kriegler, E., Roming, N., Schwanitz, J. (2016) Future growth patterns of world regions - A GDP scenario approach. Global Environmental Change.

Luderer, G., Pietzcker, R.C., Bertram, C., Kriegler, E., Meinshausen, M., Edenhofer, O. (2013) Economic mitigation challenges: How further delay closes the door for achieving climate targets. Environmental Research Letters 8.

Meinshausen, M., Raper, S.C.B., Wigley, T.M.L. (2011a) Emulating coupled atmosphere-ocean and carbon cycle models with a simpler model, MAGICC6 - Part 1: Model description and calibration. Atmospheric Chemistry and Physics 11, 1417-1456.

Meinshausen, M., Wigley, T.M.L., Raper, S.C.B. (2011b) Emulating atmosphere-ocean and carbon cycle models with a simpler model, MAGICC6 - Part 2: Applications. Atmospheric Chemistry and Physics 11, 1457-1471.

Morita, T., Nakićenović, N.j., Robinson, J. (2000) Overview of mitigation scenarios for global climate stabilization based on new IPCC emission scenarios (SRES). Environmental Economics and Policy Studies 3, 65-88.

Moss, R.H., Edmonds, J.A., Hibbard, K.A., Manning, M.R., Rose, S.K., Van Vuuren, D.P., Carter, T.R., Emori, S., Kainuma, M., Kram, T., Meehl, G.A., Mitchell, J.F.B., Nakicenovic, N., Riahi, K., Smith, S.J., Stouffer, R.J., Thomson, A.M., Weyant, J.P., Wilbanks, T.J. (2010) The next generation of scenarios for climate change research and assessment. Nature 463, 747-756.

Nakicenovic, N., Swart, R., (2000) Special Report on Emissions Scenarios (SRES). Cambridge University Press, Cambridge, UK.

Nelson, G.C., Valin, H., Sands, R.D., Havlík, P., Ahammad, H., Deryng, D., Elliott, J., Fujimori, S., Hasegawa, T., Heyhoe, E., Kyle, P., Von Lampe, M., Lotze-Campen, H., Mason D'Croz, D., Van Meijl, H., Van Der Mensbrugghe, D., Müller, C., Popp, A., Robertson, R., Robinson, S., Schmid, E., Schmitz, C., Tabeau, A., Willenbockel, D. (2014) Climate change effects on agriculture: Economic responses to biophysical shocks. Proceedings of the National Academy of Sciences of the United States of America 111, 3274-3279.

O'Neill, B.C., Kriegler, E., Ebi, K.L., Kemp-Benedict, E., Riahi, K., Rothman, D.S., van Ruijven, B.J., van Vuuren, D.P., Birkmann, J., Kok, K., Levy, M., Solecki, W. (2016a) The roads ahead: Narratives for shared socioeconomic pathways describing world futures in the 21st century. Global Environmental Change Accepted.

O'Neill, B.C., Kriegler, E., Riahi, K., Ebi, K.L., Hallegatte, S., Carter, T.R., Mathur, R., van Vuuren, D.P. (2014) A new scenario framework for climate change research: The concept of shared socioeconomic pathways. Climatic Change 122, 387-400.

O'Neill, B.C., Tebaldi, C., van Vuuren, D., Eyring, V., Friedlingstein, P., Hurtt, G., Knutti, R., Kriegler, E., Lamarque, J.-F., Lowe, J., Meehl, J., Moss, R., Riahi, K., Sanderson, B.M. (2016b) The Scenario Model Intercomparison Project (ScenarioMIP) for CMIP6. Geosci. Model Dev. Discuss. in review.

Popp, A., Katherine Calvin, Shinichiro Fujimori, Petr Havlik, Florian Humpenöder, Elke Stehfest, Benjamin Bodirsky, Jan Philipp Dietrich, Jonathan Doelmann, Mykola Gusti, Tomoko Hasegawa, Page Kyle, Michael Obersteiner, Andrzej Tabeau, Kiyoshi Takahashi, Hugo Valin, Stephanie Waldhoff, Isabelle Weindl, Marshall Wise, Elmar Kriegler, Hermann Lotze-Campen, Oliver Fricko, Keywan Riahi, Vuuren, D.v. (submitted) Land use futures in the Shared Socio-Economic Pathways. Global Environ. Change.

Popp, A., Rose, S.K., Calvin, K., Van Vuuren, D.P., Dietrich, J.P., Wise, M., Stehfest, E., Humpenöder, F., Kyle, P., Van Vliet, J., Bauer, N., Lotze-Campen, H., Klein, D., Kriegler, E. (2014) Land-use transition for bioenergy and climate stabilization: Model comparison of drivers, impacts and interactions with other land use based mitigation options. Climatic Change 123, 495-509.

Rao, S., Zbigniew Klimont, Steven J Smith, Rita Van Dingenen, Frank Dentener, Lex Bouwman, Benjamin Bodirsky, Katherine Calvin, Laurent Drouet, Oliver Fricko, Shinichiro Fujimori, Gunnar Luderer, David Gernaat, Petr Havlik, Mathijs Harmsen, Tomoko Hasegawa, Chris Heyes, Jérôme Hilaire, Toshihiko Masui, Lara Aleluia Reis, Elke Stehfest, Jessica Strefler, Sietske van der Sluis, Tavoni, M., Riahi, K., Vuren, D.v. (submitted) Future Air Pollution in the Shared Socio-Economic Pathways.

Ren, X., Weitzel M, O'Neill B, Lawrence P, Meiyappan P, Levis S, Balistreri EJ, M, D., (2015) Avoided economic impacts of climate change on agriculture: Integrating a land surface model (CLM) with a global economic model (iPETS), Working Paper. Colorado School of Mines, Division of Economics and Business.

Riahi, K., Kriegler, E., Johnson, N., Bertram, C., den Elzen, M., Eom, J., Schaeffer, M., Edmonds, J., Isaac, M., Krey, V., Longden, T., Luderer, G., Méjean, A., McCollum, D.L., Mima, S., Turton, H., van Vuuren, D.P., Wada, K., Bosetti, V., Capros, P., Criqui, P., Hamdi-Cherif, M., Kainuma, M., Edenhofer, O. (2015) Locked into Copenhagen pledges - Implications of short-term emission targets for the cost and feasibility of long-term climate goals. Technological Forecasting and Social Change 90, 8-23.

Rogelj, J., Luderer, G., Pietzcker, R.C., Kriegler, E., Schaeffer, M., Krey, V., Riahi, K. (2015) Energy system transformations for limiting end-of-century warming to below 1.5 °C. Nature Climate Change 5, 519-527.

Rogelj, J., McCollum, D.L., O'Neill, B.C., Riahi, K. (2013a) 2020 emissions levels required to limit warming to below 2°C. Nature Climate Change 3, 405-412.

Rogelj, J., McCollum, D.L., Reisinger, A., Meinshausen, M., Riahi, K. (2013b) Probabilistic cost estimates for climate change mitigation. Nature 493, 79-83.

Schmitz, C., van Meijl, H., Kyle, P., Nelson, G.C., Fujimori, S., Gurgel, A., Havlik, P., Heyhoe, E., d'Croz, D.M., Popp, A., Sands, R., Tabeau, A., van der Mensbrugghe, D., von Lampe, M., Wise, M., Blanc, E., Hasegawa, T., Kavallari, A., Valin, H. (2014) Land-use change trajectories up to 2050: Insights from a global agro-economic model comparison. Agricultural Economics (United Kingdom) 45, 69-84.

Smith, P., Gregory, P.J., Van Vuuren, D., Obersteiner, M., Havlík, P., Rounsevell, M., Woods, J., Stehfest, E., Bellarby, J. (2010) Competition for land. Philosophical Transactions of the Royal Society B: Biological Sciences 365, 2941-2957.

Tavoni, M., Kriegler, E., Riahi, K., Van Vuuren, D.P., Aboumahboub, T., Bowen, A., Calvin, K., Campiglio, E., Kober, T., Jewell, J., Luderer, G., Marangoni, G., McCollum, D., Van Sluisveld, M., Zimmer, A., Van Der Zwaan, B. (2015) Post-2020 climate agreements in the major economies assessed in the light of global models. Nature Climate Change 5, 119-126.

Taylor, K.E., Stouffer, R.J., Meehl, G.A. (2012) An overview of CMIP5 and the experiment design. Bulletin of the American Meteorological Society 93, 485-498.

UN (2014) United Nations, World Urbanization Prospects: The 2014 Revision. United Nations Publication, New York

UNFCCC (2015) INDCs as communicated by Parties.

van Ruijven, B., Levy, M., Agrawal, A., Biermann, F., Birkmann, J., Carter, T., Ebi, K., Garschagen, M., Jones, B., Jones, R., Kemp-Benedict, E., Kok, M., Kok, K., Lemos, M., Lucas, P., Orlove, B., Pachauri, S., Parris, T., Patwardhan, A., Petersen, A., Preston, B., Ribot, J., Rothman, D., Schweizer, V. (2014) Enhancing the relevance of Shared Socioeconomic Pathways for climate change impacts, adaptation and vulnerability research. Climatic Change 122, 481-494.

van Vuuren, D.P., Carter, T.R. (2014) Climate and socio-economic scenarios for climate change research and assessment: Reconciling the new with the ol. Climatic Change 122, 415-429.

van Vuuren, D.P., Edmonds, J., Kainuma, M., Riahi, K., Thomson, A., Hibbard, K., Hurtt, G.C., Kram, T., Krey, V., Lamarque, J.F., Masui, T., Meinshausen, M., Nakicenovic, N., Smith, S.J., Rose, S.K. (2011) The representative concentration pathways: An overview. Climatic Change 109, 5-31.

van Vuuren, D.P., Elke Stehfest, David Gernaat, Jonathan Doelman, Maarten van Berg, Mathijs Harmsen, H.-S.d.B., Lex Bouwman, Vassilis Daioglou, Oreane Edelenbosch, Bastien Girod, Tom Kram, Luis Lassaletta, Paul Lucas, Hans van Meijl, Christoph Müller, Bas van Ruijven, Andrzej Tabeau (submitted) Energy, land-use and greenhouse gas emissions trajectories under a green growth paradigm. . Global Environ. Change,.

van Vuuren, D.P., Kriegler, E., O'Neill, B.C., Ebi, K.L., Riahi, K., Carter, T.R., Edmonds, J., Hallegatte, S., Kram, T., Mathur, R., Winkler, H. (2014) A new scenario framework for Climate Change Research: Scenario matrix architecture. Climatic Change 122, 373-386.

Van Vuuren, D.P., Riahi, K., Moss, R., Edmonds, J., Thomson, A., Nakicenovic, N., Kram, T., Berkhout, F., Swart, R., Janetos, A., Rose, S.K., Arnell, N. (2012) A proposal for a new scenario framework to support research and assessment in different climate research communities. Global Environmental Change 22, 21-35.

Victor, D.G., Kennel, C.F. (2014) Climate policy: Ditch the 2°C warming goal. Nature 514, 30-31.

Von Lampe, M., Willenbockel, D., Ahammad, H., Blanc, E., Cai, Y., Calvin, K., Fujimori, S., Hasegawa, T., Havlik, P., Heyhoe, E., Kyle, P., Lotze-Campen, H., Mason d'Croz, D., Nelson, G.C., Sands, R.D., Schmitz, C., Tabeau, A., Valin, H., van der Mensbrugghe, D., van Meijl, H. (2014) Why do global long-term scenarios for agriculture differ? An overview of the AgMIP global economic model intercomparison. Agricultural Economics (United Kingdom) 45, 3-20.