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Land-use futures in the shared socio-economic pathways

Alexander Popp^{a,*}, Katherine Calvin^b, Shinichiro Fujimori^c, Petr Havlik^d, Florian Humpenöder^a, Elke Stehfest^e, Benjamin Leon Bodirsky^{a,h}, Jan Philipp Dietrich^a, Jonathan C. Doelmann^e, Mykola Gusti^{d,i}, Tomoko Hasegawa^c, Page Kyle^b, Michael Obersteiner^d, Andrzej Tabeau^g, Kiyoshi Takahashi^c, Hugo Valin^d, Stephanie Waldhoff^b, Isabelle Weindl^{a,j}, Marshall Wise^b, Elmar Kriegler^a, Hermann Lotze-Campen^{a,k}, Oliver Fricko^d, Keywan Riahi^{d,f}, Detlef P. van Vuuren^{f,l}

^a Potsdam Institute for Climate Impact Research (PIK), PO Box 60 12 03, 14412 Potsdam, Germany

^b Pacific Northwest National Laboratory, Joint Global Change Research Institute at the University of Maryland–College Park, 5825 University Research Court, Suite 3500, College Park, MD 20740, USA

^c National Institute for Environmental Studies (NIES), Japan

^d International Institute for Applied Systems Analysis (IIASA), Austria

^e PBL Netherlands Environmental Assessment Agency, Postbus 30314, 2500 GH The Hague, The Netherlands

^f Graz University of Technology, Austria

^g Wageningen Economic Research part of Wageningen University & Research, The Netherlands

^h Commonwealth Scientific and Industrial Research Organisation, St. Lucia, Australia

ⁱ Lviv Polytechnic National University, 12 Bandera street, 79013 Lviv, Ukraine

^j Leibniz Institute for Agricultural Engineering and Bioeconomy (ATB), Max-Eyth-Allee 100, 14469 Potsdam, Germany

^k Humboldt-University of Berlin, 10099 Berlin, Germany

^l Copernicus Institute for Sustainable Development, Utrecht University, Heidelberglaan 2, 3584 CS Utrecht, The Netherlands

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ABSTRACT

In the future, the land system will be facing new intersecting challenges. While food demand, especially for resource-intensive livestock based commodities, is expected to increase, the terrestrial system has large potentials for climate change mitigation through improved agricultural management, providing biomass for bioenergy, and conserving or even enhancing carbon stocks of ecosystems. However, uncertainties in future socio-economic land use drivers may result in very different land-use dynamics and consequences for land-based ecosystem services. This is the first study with a systematic interpretation of the Shared Socio-Economic Pathways (SSPs) in terms of possible land-use changes and their consequences for the agricultural system, food provision and prices as well as greenhouse gas emissions. Therefore, five alternative Integrated Assessment Models with distinctive land-use modules have been used for the translation of the SSP narratives into quantitative projections. The model results reflect the general storylines of the SSPs and indicate a broad range of potential land-use futures with global agricultural land of 4900 mio ha in 2005 decreasing by 810 mio ha until 2100 at the lower (SSP1) and increasing by 1080 mio ha (SSP3) at the upper end. Greenhouse gas emissions from land use and land use change, as a direct outcome of these diverse land-use dynamics, and agricultural production systems differ strongly across SSPs (e.g. cumulative land use change emissions between 2005 and 2100 range from –54 to 402 Gt CO₂). The inclusion of land-based mitigation efforts, particularly those in the most ambitious mitigation scenarios, further broadens the range of potential land futures and can strongly affect greenhouse gas dynamics and food prices. In general, it can be concluded that low demand for agricultural commodities, rapid growth in agricultural productivity and globalized trade, all most pronounced in a SSP1 world, have the potential to enhance the extent of natural ecosystems, lead to lowest greenhouse gas emissions from the land system and decrease food prices over time. The SSP-based land use pathways presented in this paper aim at supporting future climate research and provide the basis for further regional integrated assessments, biodiversity research and climate impact analysis.

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* Corresponding author.

E-mail address: popp@pik-potsdam.de (A. Popp).

1. Introduction

Agricultural land-use activities have significantly reshaped our planet, as approximately 40% of the terrestrial surface is currently under agricultural use, either as cropland or pasture (Kareiva et al., 2007; FAO 2014). Historically, the food and material needs of a growing population have been met through expansions in cultivated agricultural area and an increase in agricultural productivity through increases in modern inputs such as new crop varieties, machinery, irrigation water, fertilizer and pesticides (Foley et al., 2005; Rudel et al., 2009; Tilman et al., 2011; Burney et al., 2010; Steinfeld and Gerber, 2010). While the benefits of agriculture to society have been immense, the increase in agricultural production has also been a source of environmental degradation including the loss of biodiversity and wildlife habitats (Carpenter et al., 2009), nutrient run-off (Bodirsky et al., 2014), and emissions of greenhouse gases (GHGs) (Smith et al., 2013).

In the future, the world will be facing new interconnected challenges. Global income levels are expected to increase, as will global population at least through 2050. As a result, an increase in food consumption and a greater demand for livestock-based products is likely (Bodirsky et al., 2015), increasing environmental pressure from agriculture even further. Currently, land use and land-use change are responsible for approximately a quarter of global GHG emissions, largely from tropical deforestation, methane emissions from livestock and rice cultivation, and nitrous oxide emissions from fertilized soils and manure management (Tubiello et al., 2015). This also means that land use management plays a key role in mitigation strategies. In addition to potential emission control mechanisms, such as avoided deforestation and improved agricultural management, the land system could also contribute to climate change mitigation by enhanced carbon dioxide removal (CDR) through afforestation and bioenergy crop production combined with carbon capture and sequestration (BECCS) (Obersteiner et al., 2001; Smith et al., 2013; Humpeöder et al., 2014). Such additional pressures could pose huge challenges for the sustainability of future land systems.

There is uncertainty as to how the demand for agricultural goods will evolve in the future (Valin et al., 2014) and how land use dynamics will respond to an anticipated increase in the demand for ecosystem services (Schmitz et al., 2014). These demands depend strongly on future trends in population growth, dietary preferences, trade, demand for non-food products such as bioenergy, future developments in agricultural yields, and relevant policies. Over time, these uncertainties may result in very different land-use patterns, associated emissions and food prices (von Lampe et al., 2014). Scenario analysis of alternative plausible futures is often used as a tool to explore and evaluate the extensive uncertainties associated with possible future developments (van Vuuren et al., 2012). Most studies of the future environment, including the climate change scenarios of the Intergovernmental Panel on Climate Change (IPCC) summarised in the Special Report on Emissions Scenarios (Nakicenovic and Swart, 2000) and the Millennium Ecosystem Assessment (Carpenter and Pingali, 2005), have used storylines in combination with models to provide scenarios of plausible alternative futures. The objective of these storylines and scenarios is to assess the variation in possible futures and to provide insights into the magnitude and uncertainty of future changes.

Recently, a new set of scenarios has been proposed that are organized around two important dimensions: the extent of climate change and possible future socio-economic conditions. The amount of climate change in the future was explored through the development of different representative concentration pathways (RCPs, (Van Vuuren et al., 2011)). The possible future socio-economic conditions are described in the Shared Socio-economic

Pathways (SSPs (O'Neill et al., this Special Issue)), that can be combined with the RCPs in a scenario matrix architecture (Van Vuuren et al., 2016). The SSPs provide five different stories of future socio-economic development, including possible trends in agriculture and land use (O'Neill et al., this Special Issue). In each of the SSPs, climate policies can be introduced to reduce emissions and to enhance carbon uptake to reach radiative forcing level targets consistent with the RCP pathways (Kriegler et al., 2014).

Clearly, a new set of scenarios relevant for climate research will need to address development in the land-use system in detail. In this paper, we describe how a set of Integrated Assessment Models (IAMs) have elaborated the initial storylines of the SSPs and how the results of these models compare to each other. To this end, we will first present relevant aspects of the SSP framework for the land system. Then, we describe possible future pathways of land use, including the resulting GHG emissions and food prices, under different SSPs and climate policy assumptions based on the implementation of the narratives and quantitative elements of the SSPs into the IAMs.

2. Methods—short description of models & markers

2.1. SSP storylines for the land use sector

The SSPs provide a framework for developing new socio-economic scenarios for use in global climate change studies but also for assessments of the broader sustainable development context (Riahi, this Special Issue), (Ebi et al., 2013; Vuuren et al., 2013; O'Neill et al., 2013). The SSPs depict five different global futures (SSP 1–5) with substantially different socio-economic conditions that aim to reflect different socio-economic challenges to mitigation and adaptation. On the most fundamental level, each SSP is described by a narrative (O'Neill et al., this Special Issue) including their challenges to adaptation and mitigation. SSP1 describes a future pathway with low challenges for adaptation and mitigation, whereas in SSP3 both challenges are high. In addition, two “asymmetric cases” are designed, comprising a future in which high challenges to mitigation is combined with low challenges to adaptation (SSP5), and a case where the opposite is true (SSP4). A fifth narrative (SSP2) describes medium challenges of both kinds and is intended to represent a future in which development trends are not extreme in any of the dimensions, but rather follow middle-of-the-road pathways.

These SSP baseline storylines, and their respective implementations in five IAMs, describe socio-economic developments without the assumption of climate policies and excluding climate change and CO₂ fertilization effects. The exclusion of climate policy and climate change is consistent with the idea that these baseline pathways should be used in subsequent studies of mitigation, adaptation and climate impacts. In a next step, SSP-specific socio-economic baseline conditions can be combined with climate policy to achieve RCP-specific climate forcing levels and determine the ability and efforts to mitigate climate change (Vuuren et al., 2013) and the associated contributions of the land use sector. In each of the SSPs, climate policies can be introduced to reduce emissions or to enhance carbon uptake to reach radiative forcing level targets consistent with the RCPs (Kriegler et al., 2012). The climate policies vary across SSPs in terms of international cooperation, timing and sectoral participation in an effort to be consistent with the general and sector-specific SSP storylines. To this end, shared climate Policy Assumptions (SPAs, (Kriegler et al., 2014)), capturing key climate policy attributes such as targets, instruments and obstacles have been developed to guide the implementation of climate policies in the IAMs. In this section we present summaries of the five narratives focusing on the land sector (see also Table 1 for overview):

Table 1
Overview on land use description for the 5 SSP scenarios.

	SSP 1	SSP 2	SSP 3	SSP 4	SSP 5
Land-use change regulation	Strong regulation to avoid environmental tradeoffs	Medium regulation; slow decline in the rate of deforestation	Limited regulation; continued deforestation	Highly regulated in MICs and HICs; lack of regulation in LICs lead to high deforestation rates	Medium regulation; slow decline in the rate of deforestation
Land productivity growth	High improvements in agricultural productivity; rapid diffusion of best practices	Medium pace of technological change	Low technology development	Productivity high for large scale industrial farming, low for small-scale farming	Highly managed, resource-intensive; rapid increase in productivity
Environmental Impact of food consumption	Low growth in food consumption, low-meat diets	Material-intensive consumption, medium meat consumption	Resource-intensive consumption	Elites: high consumption lifestyles; Rest: low consumption	Material-intensive consumption, meat-rich diets
International Trade	Moderate	Moderate	Strongly constrained	Moderate	High, with regional specialization in production
Globalization	Connected markets, regional production	Semi-open globalized economy	De-globalizing, regional security	Globally connected elites	Strongly globalized
Land-based mitigation policies	No delay in international cooperation for climate change mitigation. Full participation of the land use sector	Delayed international cooperation for climate change mitigation. Partial participation of the land use sector	Heavily delayed international cooperation for climate change mitigation. Limited participation of the land use sector	No delay in international cooperation for climate change mitigation. Partial participation of the land use sector	Delayed international cooperation for climate change mitigation. Full participation of the land use sector

2.1.1. SSP1: sustainability—taking the green road

The world shifts gradually, but pervasively, toward a more sustainable path, emphasizing more inclusive development that respects perceived environmental boundaries. Land use is strongly regulated, e.g. tropical deforestation rates are strongly reduced. Crop yields are rapidly increasing in low- and medium-income regions, leading to a faster catching-up with high income countries. Healthy diets with low animal-calorie shares and low waste prevail. In an open, globalized economy, food is traded internationally. In SSP1, international cooperation for climate change mitigation starts early (after 2020). All land use emissions are priced at the level of carbon prices in the energy sector.

2.1.2. SSP2: middle of the road

The world follows a path in which social, economic, and technological trends do not shift markedly from historical patterns. Land use change is incompletely regulated, i.e. tropical deforestation continues, although at slowly declining rates over time. Rates of crop yield increase decline slowly over time, but low-income regions catch up to a certain extent. Caloric consumption and animal calorie shares converge slowly towards high levels. International trade remains to large extent regionalized. In SSP2, international cooperation for climate change mitigation is delayed due to a transition phase to a uniform carbon price until 2040. In this transition phase, emissions from agricultural production are priced at the level of energy sector emissions, while avoided deforestation and afforestation are not incentivized before 2030.

2.1.3. SSP3: regional rivalry—a rocky road

A resurgent nationalism, concerns about competitiveness and security, and regional conflicts push countries to increasingly focus on domestic or, at most, regional issues, including food and energy security. Land use change is hardly regulated. Rates of crop yield increase decline strongly over time, especially due to very limited transfer of new agricultural technologies to developing countries. Unhealthy diets with high animal shares and high food waste prevail. A regionalized world leads to reduced trade flows for agricultural goods. In SSP3, forest mitigation activities and abatement of agricultural GHG emissions are limited due to major

implementation barriers such as low institutional capacities in developing countries. In addition, they are delayed as a consequence of low international cooperation. In 2020, high income countries start the transition to a uniform carbon price until 2040, whereas low income countries start in 2030 and converge until 2050.

2.1.4. SSP4: Inequality—A road divided

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. Land use change is strongly regulated in high income countries, but tropical deforestation still occurs in poor countries. High income countries achieve high crop yield increases, while low income countries remain relatively unproductive in agriculture. Caloric consumption and animal calorie shares converge towards medium levels. Food trade is globalized, but access to markets is limited in poor countries, increasing vulnerability for non-connected population groups. In SSP4, international cooperation for climate change mitigation starts early (after 2020). But emissions from agricultural and land use are incompletely priced, with limited incentives for avoided deforestation and afforestation before 2030.

2.1.5. SSP5: fossil-fueled development—taking the highway

Driven by the economic success of industrialized and emerging economies, 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. Land use change is incompletely regulated, i.e. tropical deforestation continues, although at slowly declining rates over time. Crop yields are rapidly increasing. Unhealthy diets with high animal shares and high waste prevail. Barriers to international trade are strongly reduced, and strong globalization leads to high levels of international trade. In SSP5, all land use emissions are priced at the level of carbon prices in the energy sector. But in contrast to SSP1, international cooperation for climate change mitigation is delayed due to a transition phase to a uniform carbon price until 2040.

2.2. Scenario quantification

For this SSP assessment, five integrated assessment models (IAMs) have been applied to derive a quantitative description of the storylines, namely AIM (Fujimori et al., 2014, 2016), GCAM (Wise et al., 2014), IMAGE (Stehfest et al., 2014), MESSAGE-GLOBIOM (Kindermann et al., 2006; Havlík et al., 2014; Riahi et al., 2012) and REMIND/MAGPIE (Popp et al., 2011, 2014). All of these models have in common that they contain land-use modules, which differ, however, in their representation and parametrization of biogeochemical, biophysical and socio-economic processes. More detailed descriptions of the individual models can be found in the SOM (see Section 1: Overview on integrated modeling frameworks), as well as in the respective papers on the SSP implementations by the different teams within this Special Issue (Calvin et al., this Special Issue; Fricko et al., this Special Issue; Fujimori et al., this Special Issue; Kriegler et al., this Special Issue; van Vuuren et al., this Special Issue). These models are driven by the same projections of economic growth (Dellink et al., this special issue; Dietrich et al., 2014) and population (KC and Lutz, this special issue), developed for the SSPs. For other characteristics of the storylines (Table 1), the modeling teams made their own assumptions on how to best represent the described trends of these drivers (see table on IAM implementations in the SOM).

As future development of parameters like crop yields and livestock intensification are known to strongly influence future land use, this limited harmonization inevitably will lead to a rather wide range in the outcomes across IAMs for one specific SSP. However, this strategy of limited quantitative harmonization was intentional, in order to explore uncertainty in scenario implementation and model behavior. In addition, the different structures of the models would not allow for a precise harmonization in this respect. For each of the five SSPs, the implementation by one specific IAM has been selected as the so-called marker scenario. The selection of the 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 storyline. Identifying the markers involved an iterative process with multiple rounds of internal and external reviews of energy system, emissions and land use model representations (Riahi et al., this special issue). Furthermore, additional realizations of the SSPs have also been computed by non-marker IAMs (see Table 2 for an overview) since they provide insights into possible alternative projections of the same qualitative storyline, including a first-order estimate of uncertainties attending to model structure and interpretation/implementation of the storylines. In this paper, we concentrate on the detailed presentation and discussion of the SSP marker scenarios for the baseline case without climate change mitigation, as well as the RCP4.5 and the RCP2.6 mitigation cases. Additionally, we indicate the range across all quantifications (marker and non-markers). Finally, we note throughout the paper where the selection of marker models may influence the qualitative conclusions drawn.

3. Results

In this section, we describe SSP-specific dynamics of agricultural demand, production and trade, land use, agricultural intensification, GHG emissions and food prices at the global and regional level. Due to differences in base year data sources, and large uncertainties in historical data, land use outputs differ more between the IAMs than for example energy outputs (Bauer et al., this special issue). Therefore, in this paper, we focus on changes over time compared to 2005, as opposed to absolute values. More detailed marker model output including model-specific data for the 2005 base year and regional outcomes are shown in the SI. All data can also be accessed over the interactive public SSP web-database hosted by IIASA (<https://secure.iiasa.ac.at/web-apps/ene/SspDb>). Data is shown and discussed in this paper for five aggregate regions: (1) OECD90 countries and new EU member states and candidates (OECD), (2) reforming economies of the Former Soviet Union (excluding EU member states; REF), (3) countries of the Middle East and Africa (MAF), (4) countries of Latin America and the Caribbean (LAM) and (5) Asian countries with the exception of the Middle East, Japan and Former Soviet Union states (ASIA). We mainly describe results along the baseline and two selected mitigation cases (RCP4.5 & RCP2.6). Please note that SSP3 was infeasible for RCP2.6, and therefore does not show up in the respective results. While most of the discussion focuses on quantitative results from the marker scenarios, we indicate where results differ across models throughout this section (see also Fig SI16–SI19 and Tab SI1 and Tab SI2).

3.1. Demand, production & trade

Global population has risen from 3.3 billion in 1965 to 6.5 billion in 2005 (Worldbank, 2015). This growth has been accompanied by increased per capita food and feed demand (2310 kcal/cap/day in 1965 to 2763 kcal/cap/day in 2005 (FAOSTAT 2015)), resulting in total crop production of 3750 million t DM in 2005 and 250 million t DM in 2005 of livestock products. Fig. 1 shows this historical development (FAO 2014), as well as the change of global demand for food and feed crops and livestock products in the different SSPs from 2005 to 2100. Future demand depends on population dynamics (Fig SI1) and per capita demand (Fig SI2), which in turn depends on income, preferences, and food price sensitivities.

In the **SSP2** baseline scenario, population dynamics, per capita caloric consumption and animal calorie shares increase moderately. As a consequence, global demand for crop (plus 2860 mio t DM in 2100) and livestock products (plus 235 mio t DM in 2100) increases moderately in SSP2 with the highest shares and increases in demand over time in ASIA (Fig SI3 and SI6). Production remains fairly regionalized (Fig SI4 and SI7) and trade with agricultural goods grows slowly (Fig SI5 and SI8). In **SSP1**, due to low population increases and healthy diets with low animal-calorie shares and low food waste, food demand for crops (plus 1983 mio t DM in 2100)

Table 2
Overview of SSPs and marker teams.

Identifier	Descriptor	Marker model (institution)	Also computed by
SSP1	Sustainability	IMAGE-MAGNET (PBL, LEI)	All
SSP2	Middle-of-the-Road	MESSAGE-GLOBIOM (IIASA)	All
SSP3	Regional Rivalry	AIM/CGE (NIES)	IMAGE, MESSAGE-GLOBIOM, GCAM (only baseline)
SSP4	Inequality	GCAM (PNNL)	AIM/CGE
SSP5	Fossil-fueled Development	REMIND-MAGPIE (PIK)	AIM/CGE, GCAM

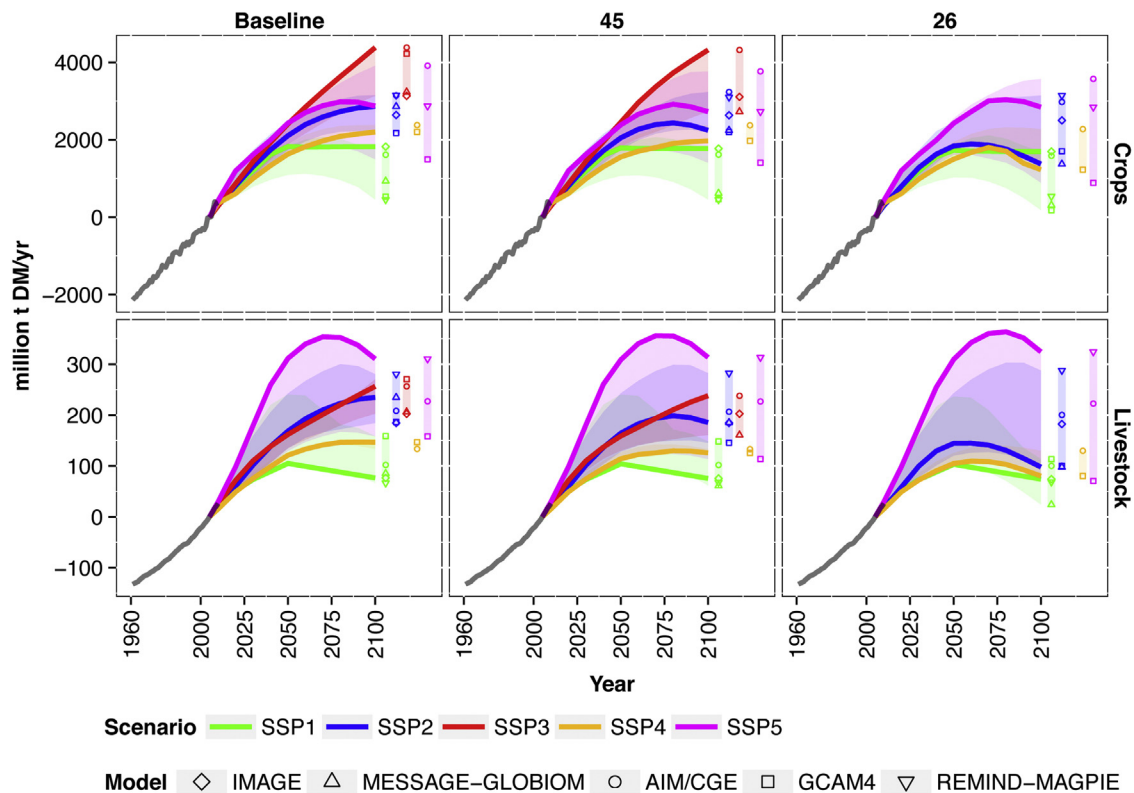


Fig. 1. Change in global demand for crops (upper row) and livestock products (lower row) of the five SSP marker scenarios for the baseline (left column), RCP4.5 (middle column) and RCP2.6 (right column) cases. Colored lines indicate the marker model results for each SSP. Colored bars indicate the range of data in 2100 across all marker and non-marker projections for each SSP (models are depicted by icon). Grey line shows historical trends based on FAO data (FAO 2014).

and livestock (plus 85 mio t DM in 2100) products increases slightly until the mid of the century and then decreases. Additionally, trade of agricultural products increases only moderately, although markets are globally connected. Here, an emphasis on domestic production reduces the incentive for specialization in agricultural production and hence limits the increase in trade volumes. In **SSP3**, very high population increases, but low economic growth drive increases in global demand for crops to higher levels than in SSP2 (plus 4384 mio t DM in 2100, mainly in MAF), and to similar levels as in SSP2 for livestock products (plus 256 mio t DM in 2100, mainly in MAF and ASIA). In such a de-globalized world, a small share of agricultural goods is traded, and when it is, highly populated regions like MAF are importers. Compared to SSP2, **SSP4** shows relatively low increases in demand of both crops (plus 2201 mio t DM in 2100) and livestock products (plus 147 mio t DM in 2100) (mainly in MAF), despite having global population growth very similar to SSP2. This difference in demand is because the increase in population in **SSP4** is mainly in low-income regions such as MAF with limited access to markets, and even more importantly because the GDP growth in these already poor regions is even slower under SSP4 than under SSP2. The high demand for crops in MAF and ASIA is met with both local production and imports from OECD and LAM. **SSP5** reaches similar levels of crop demand as SSP2 (plus 2870 mio t DM in 2100), but much higher demand for livestock products occurs in SSP5, especially in the middle of the century (plus 354 mio t DM in 2070) due to unhealthy diets with high animal shares and high shares of food waste. Part of the crop demand increases in SSP5 are associated with intensified livestock production systems and higher feed crop use. In the strongly globalized world of SSP5, agricultural products are not necessarily produced domestically. Instead, ASIA becomes the most important exporter for crops in the latter half century and MAF the most

important exporter for livestock products due to high increases in agricultural productivity in both, livestock and crops systems.

Global results in the non-marker baseline and mitigation scenarios are largely consistent with these findings for SSP1, SSP2, and SSP3, as indicated by the limited overlap in uncertainty bars for these three scenarios. All models find lower demand in 2100 for SSP1 than SSP2, and most find higher demand in SSP3 than in SSP2 (MESSAGE-GLOBIOM has slightly smaller demand for livestock in SSP3). Models diverge with respect to crop demand in SSP4, with GCAM showing roughly equal crop demand in SSP2 and SSP4, while AIM has lower crop demand in SSP4 than in SSP2. Additionally, differences across models emerge in SSP5. Both GCAM and REMIND show lower crop demand than SSP2, while AIM shows higher. For livestock, both REMIND and AIM show higher demand in SSP5, while GCAM shows lower.

As shown in Fig. 2, demand for dedicated 2nd generation bioenergy crops plays a critical role not so much in the baseline scenario but in nearly all mitigation scenarios because it provides an option to reduce emissions in the electricity and transport sectors and allows for active carbon dioxide removal from the atmosphere if combined with carbon capture and sequestration (BECCS). Particularly in SSP5, a large amount of carbon dioxide removal is needed for limiting climate forcing to levels of 4.5 W/m² and 2.6 W/m² by the end of the century, as a result of high exploitation of abundant fossil fuel resources (Bauer et al., this special issue), the adoption of resource and energy intensive lifestyles around the world and associated high levels of GHG emissions in the baseline case. Due to strong reliance on technical solutions in SSP5, land-based CDR in SSP5 rely on BECCS leading to large scale 2nd generation bioenergy crop demand of 9364 t DM in 2100 in RCP4.5 and 23142 t DM in 2100 in RCP2.6. This dependence on bioenergy in SSP5 is consistent across marker and non-marker

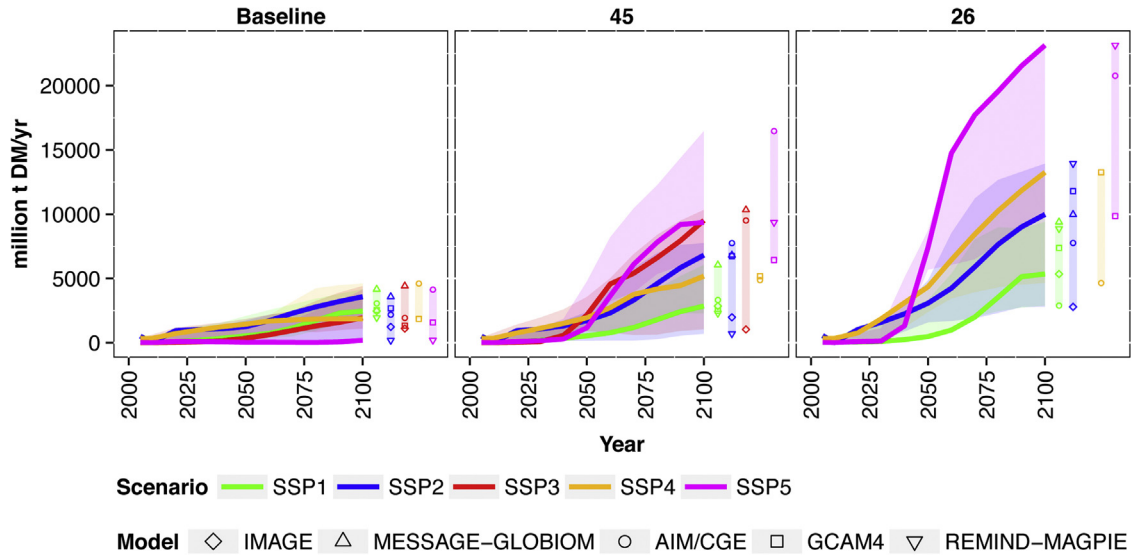


Fig. 2. Global demand for dedicated 2nd generation bioenergy crops of the five SSP marker scenarios for the baseline (left column), RCP4.5 (middle column) and RCP2.6 (right column) cases. Colored lines indicate the marker model results for each SSP. Colored bars indicate the range of data in 2100 across all marker and non-marker projections for each SSP (models are depicted by icon).

models (non-marker models show 20775 and 21132 million t DM in 2100 in RCP2.6).

The response of food demand to climate policy differs across marker and non-marker models, particularly in the RCP2.6 mitigation case. This results mainly from explicit model assumptions on high (e.g. MESSAGE-GLOBIOM) or low (e.g. REMIND-

MAGPIE, IMAGE) sensitivities of food demand to increased food prices from mitigation pressure on land. Regional mitigation pressures on the land system, such as 2nd generation bioenergy production in LAM, MAF and ASIA (Fig S19) displace agricultural production particularly in the most globalized SSP5 scenario. For example, in the SSP5 RCP2.6, trade of food and feed crops is further

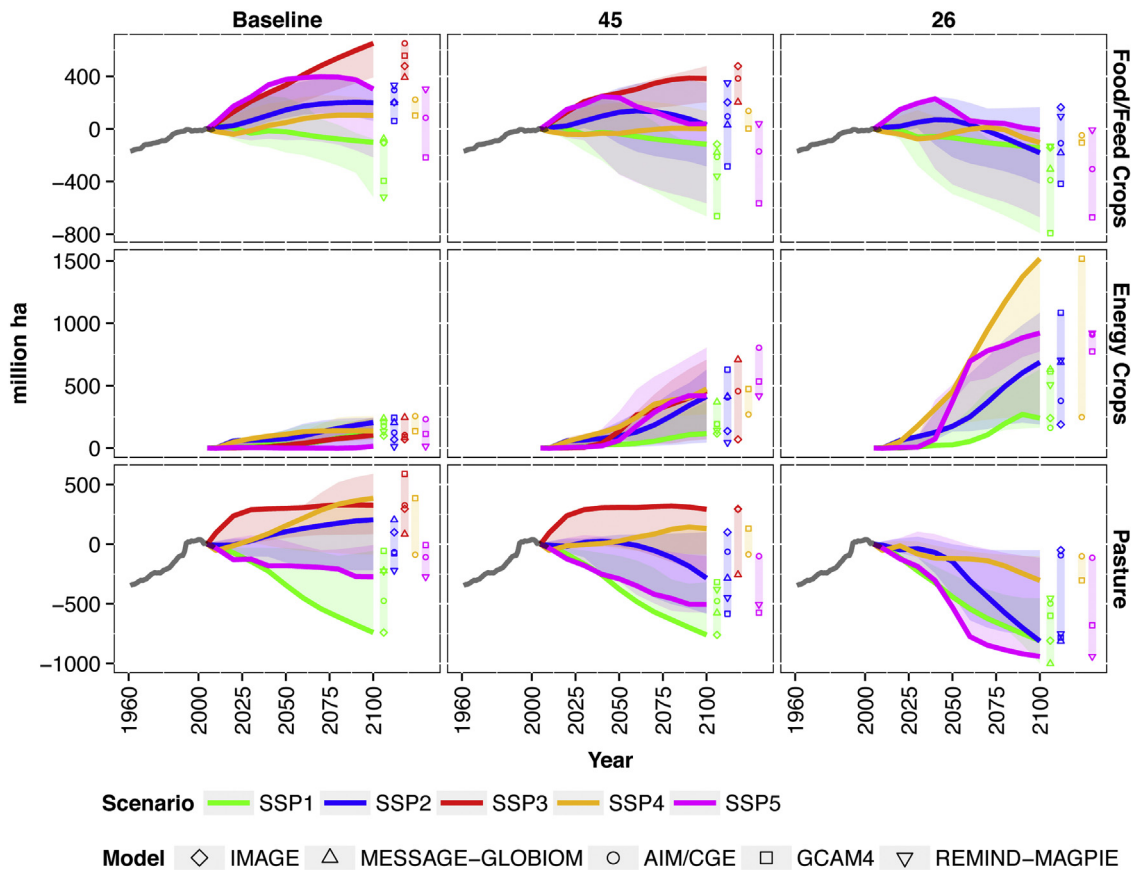


Fig. 3. Change in global land for food and feed crops (upper row), energy crops (middle row) and pasture (lower row) of the five SSP marker scenarios for the baseline (left column), RCP4.5 (middle column) and RCP2.6 (right column) cases. Colored lines indicate the marker model results for each SSP. Colored bars indicate the range of data in 2100 across all marker and non-marker projections for each SSP (models are depicted by icon). Grey line shows historical trends based on FAO data (FAO 2014).

expanded compared to the Ref scenario (Fig SI4 & SI5), and livestock production is shifted from MAF mainly to ASIA and LAM (Fig SI7 & SI9).

3.2. Trends in land use and agricultural intensification

According to the Food and Agriculture Organization of the United Nations (FAO 2014), 4.9 billion hectares (approximately 40% of the land surface) was under agricultural use in 2005, either as cropland (1.5 billion hectares) or pasture (3.4 billion hectares). Historically, in the era before industrial fertilizers, increases in agricultural production were mainly achieved by expanding cropland and pasture land into forests and natural ecosystems. Today, in some regions such as Sub-Sahara Africa and Latin America, agricultural expansion has continued, at the cost of 110 million hectares of natural forests between 1990 and 2005 (Fig. 4). However, over the last few decades, agricultural intensification was the major source of increases in global crop production, with world average cereal yield having increased by factor of 2.5 from 1.3 t/ha in 1960 to 3.3 t/ha in 2005.

The baseline SSPs cover a very wide-range of land-use futures, illustrated by the trends shown in Fig. 3 (agricultural land), Fig. 4 (forests and other natural land), and Fig. 5 (agricultural yield increases). Figures SI10–SI12 indicate that the models have similar global land cover at the initial time, but notably differ in their regional classification of land use types, as well as in their regional allocation of total land.

The use of cropland for food and feed production increases moderately in SSP2 (plus 231 mio ha between 2005 and 2100), due to relatively high demand for food and feed crops, combined with

high yield increases (by a factor of 1.6 between 2005 and 2100). Pasture area increases strongly in SSP2 (plus 204 mio ha until 2100). Agricultural expansion mainly happens in MAF and LAM (Fig SI10) as a result of medium demand for livestock products satisfied mostly through rather extensive livestock production systems. These increases in agricultural land happen at the expense of forest areas (LAM) and other natural land (MAF). In SSP1, with one of the lowest demand for agricultural goods and high intensification of agricultural production, agricultural land for both, crops and pasture, decreases, and is significantly lower than in the other SSPs. As a consequence of such agricultural abandonment and regrowth of natural vegetation, other natural land and forests expand strongly in all regions. The highest increases in pasture and cropland for food and feed production (mainly in MAF and LAM at the cost of forests and other natural land) are observed in SSP3, mostly driven by an increasing global population combined with low agricultural intensification. SSP4 shows minor increases of cropland and strong increases of pastureland (mainly in MAF) at the expense of forests. These increases in agricultural land are caused by a similar reasons to those noted for SSP3, as low income regions such as MAF in SSP4 show high population growth while remaining relatively unproductive in agriculture. As a result of production increases in unproductive regions, global average crop yields decline the second half of the century, despite continued yield improvements in all regions. SSP5 shows an increasing use of cropland until 2050 (mainly in ASIA, LAM & MAF) which then decreases towards medium levels in 2100 and a decline in pasture throughout the century. Contraction of agricultural land in SSP5 occurs as population decreases and consumption stabilizes at high levels per capita and at the same time production of livestock

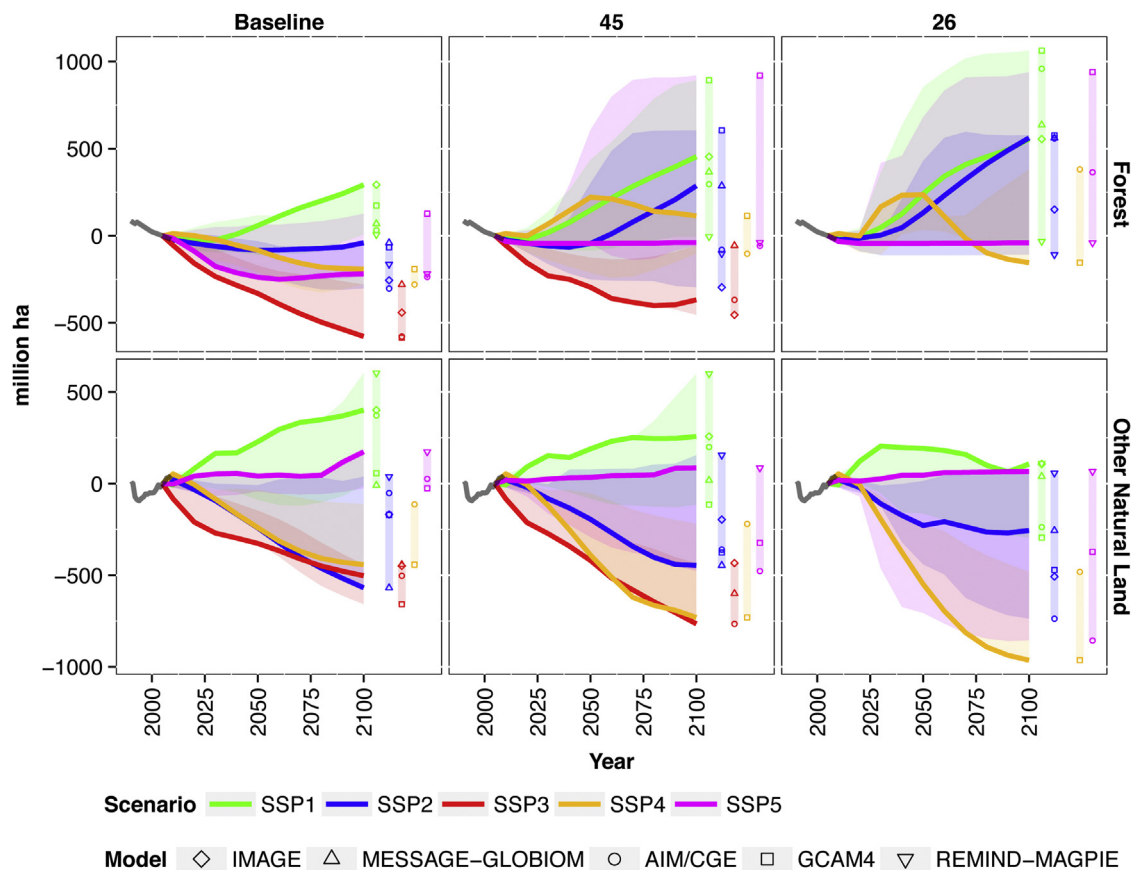


Fig. 4. Change in global land for forest (upper row) and other natural land (lower row) of the five SSP marker scenarios for the baseline (left column), RCP4.5 (middle column) and RCP2.6 (right column) cases. Colored lines indicate the marker model results for each SSP. Colored bars indicate the range of data in 2100 across all marker and non-marker projections for each SSP (models are depicted by icon). Grey line shows historical trends based on FAO data (FAO 2014).

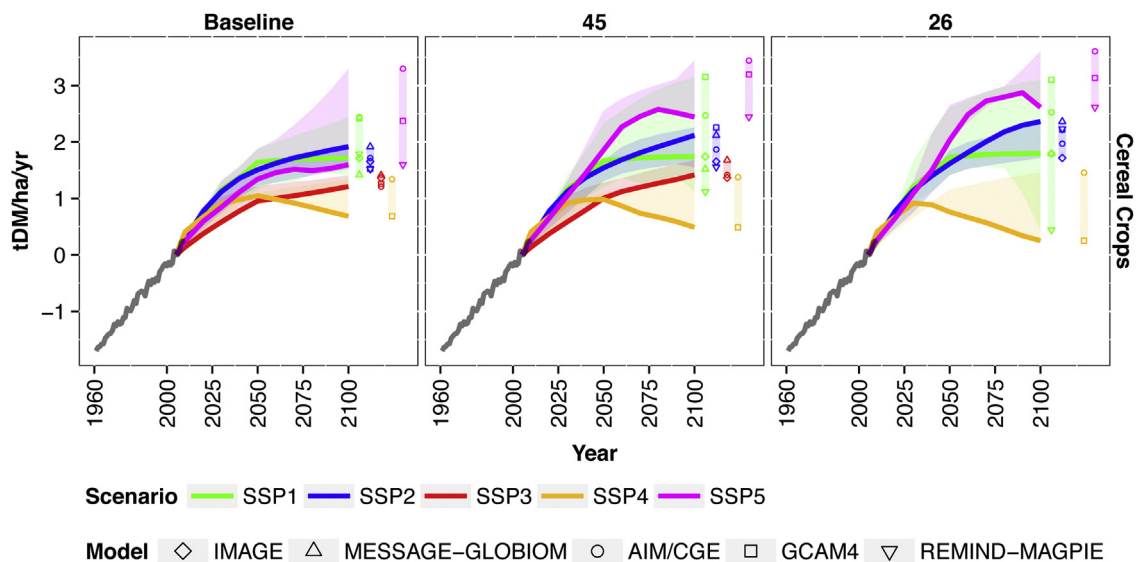


Fig. 5. Change in global cereal crop yields of the five SSP marker scenarios for the baseline (left column), RCP4.5 (middle column) and RCP2.6 (right column) cases. Colored lines indicate the marker model results for each SSP. Colored bars indicate the range of data in 2100 across all marker and non-marker projections for each SSP (models are depicted by icon). Grey line shows historical trends based on FAO data (FAO 2014).

products is met through a shift from extensive to more intensive animal husbandry.

These findings are fairly consistent across baseline marker and non-marker scenarios, with all models showing lower cropland area in SSP1 and higher cropland area in SSP3 than in SSP2 (see also Fig SI16 and SI17 as well as Tab SI1 and SI2). Forest area, in contrast, is largest in SSP1 and smallest in SSP3 in all models (with the exception of IMAGE SSP3). Land cover in SSP4 and SSP5 are more similar to SSP2 in most cases; however, models diverge in some instances. For example, GCAM has significantly larger pasture area in SSP4 than in SSP2, while AIM shows roughly equal areas in the two scenarios.

In most of the mitigation cases, dynamics of agricultural land for food and feed production are affected by land demanding mitigation options such as bioenergy, avoided deforestation or afforestation. The clear exception is in SSP3 where major implementation barriers for land-based mitigation are assumed to occur and where no climate stabilization levels of RCP 2.6 can be attained. Avoided deforestation restricts agricultural expansion in most of the SSPs, with the exception of SSP3 and the low-income regions of SSP4 (MAF and ASIA) due to weak land use change regulation (Fig SI11 and SI12). The land system can also contribute to climate change mitigation by increasing carbon stocks. This trend is observed particularly in the very ambitious mitigation target of RCP2.6, which relies on land-based carbon dioxide removal options such as afforestation or BECCS. Here, afforestation for carbon sequestration increases global forest areas in 2100, compared to Ref, by 62 mio ha in SSP1 and by 601 mio ha in SSP2 (mainly in MAF and LAM) (see also Fig SI18 and SI19). Bio-energy plays a critical role in nearly all mitigation but also in the baseline scenarios. The SSPs allocate between 142 million ha (SSP1) and 473 million ha (SSP4) in the RCP4.5 and between 270 million ha (SSP1) and 1517 million ha (SSP4) in the RCP 2.6 mitigation scenario to ligno-cellulosic bioenergy crop production in 2100. Both land-based CDR strategies (afforestation and BECCS) happen at the expense of other natural land (SSP4), unprotected forests (SSP3), land for food and feed crops (SSP2, SSP4 and SSP5) and pastureland (SSP2, SSP4 and SSP5). Generally, as a result of land needed for large scale bioenergy production and afforestation programs in the mitigation scenarios, the use of land for food and feed production

and pasture is reduced, following considerable agricultural intensification (SSP5) and dietary changes (SSP2) compared to the baseline scenarios.

3.3. Projections of GHG emissions

Land-use change, mainly the conversion of tropical forests to agricultural land, is a significant source of carbon emissions accounting for approximately 12% of all anthropogenic carbon emissions from 1990 to 2010. The agricultural sector is also the largest contributor to global anthropogenic non-CO₂ GHGs. In total non-CO₂ GHG emissions from agriculture (CH₄ from enteric fermentation, rice production and animal waste management systems; N₂O from synthetic fertilizer application and animal waste management systems) are estimated to account for about 10–12% of global anthropogenic emissions in 2010 (Smith et al., 2013). Between 1970 and 2005, global agricultural CH₄ emissions grew from 128.5 Mt to 144.0 Mt CH₄/yr and global agricultural N₂O emissions from 3.3 to 5.7 Mt N₂O/yr (FAO 2014).

GHG dynamics as an outcome of land use dynamics and agricultural production systems span a broad range of potential futures with SSP3 being highest and SSP1 lowest for all GHG categories considered. In the baseline scenario of **SSP2**, global CO₂ emissions from land use change amount to 219 Gt CO₂ cumulatively between 2005 and 2100 (Fig. 6). Annual CO₂ emissions decrease steadily until the end of the century and are negative from 2080 onwards (Fig SI14). Emissions occur mainly in MAF and LAM (Fig SI14) as a result of cropland and pasture expansion and the associated loss of forests and other natural land. Carbon uptake happens from mid-century onwards, mainly due to regrowth of vegetation in ASIA. Annual CH₄ emissions from agricultural production increase by 41 Mt CH₄ between 2005 and 2050 and then remain fairly constant due to lower increases in demand, especially for livestock products, and more intensified livestock production systems associated with lower emission factors (Fig. 7). Annual N₂O emissions increase by 3.5 Mt N₂O through 2100. The lowest projected CO₂, CH₄ and N₂O emissions across all SSPs occurs in **SSP1**. Global cumulative CO₂ emissions are even negative in 2060 already (-54 Gt CO₂ until 2100) due to abandonment of agricultural land and associated carbon uptake

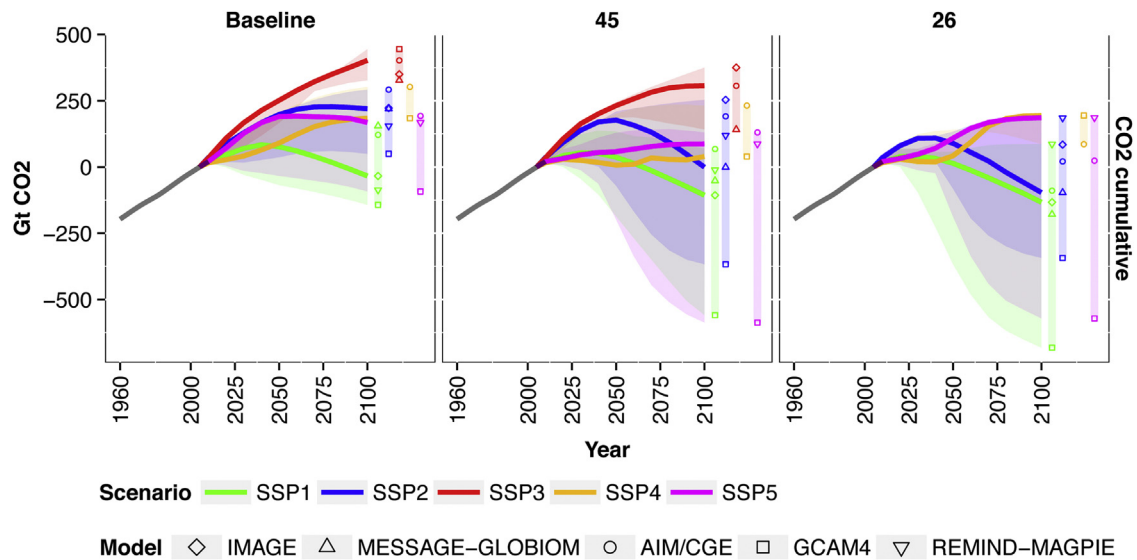


Fig. 6. Change in global cumulative land-use change emissions since 2005 of the five SSP marker scenarios for the baseline (left column), RCP4.5 (middle column) and RCP2.6 (right column) cases. Colored lines indicate the marker model results for each SSP. Colored bars indicate the range of data in 2100 across all marker and non-marker projections for each SSP (models are depicted by icon). Grey line shows historical trends based on RCP data (van Vuuren et al., 2012).

through vegetation regrowth in MAF, LAM and OECD. Low CH₄ and N₂O emissions in SSP1 are associated with generally low demand for agricultural goods, especially livestock products, and livestock production systems with high conversion efficiencies. In contrast to SSP1, the highest cumulative CO₂ emissions from land use change occur in **SSP3** (402 Gt CO₂ through 2100), as a result of very high agricultural expansion (mainly in ASIA and MAF). CH₄ emissions increase steadily until 2100 (by 238 Mt CH₄ compared to 2005) with highest contributions from ASIA and MAF driven by a combination of population growth and associated demand

increases and low intensification of agricultural production. Also N₂O emissions (mainly from MAF and ASIA) show highest increases across all scenarios (by 9.0 Mt N₂O compared to 2005). In **SSP4**, global cumulative CO₂ emissions (mainly due to forest losses in MAF) reach 183 Gt CO₂ in 2100. Annual CH₄ emissions reach 202 Mt CH₄/yr and N₂O emissions 8.2 Mt CH₄/yr in 2100. Finally, **SSP5** shows increasing cumulative CO₂ emissions until 2050 (190 Gt CO₂) that remain constant afterwards as land-use changes in ASIA, LAM and MAF and related carbon emissions come to a halt. Annual CH₄ emissions in SSP5 show highest

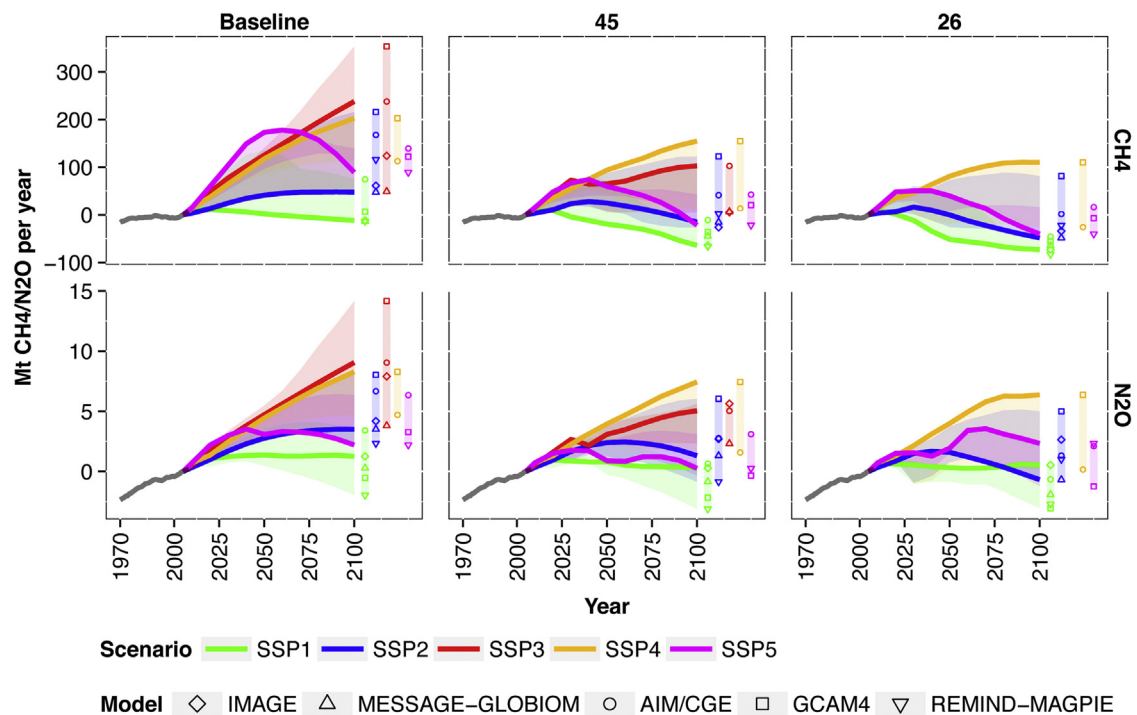


Fig. 7. Change in global agricultural CH₄ (upper row) and N₂O emissions (lower row) of the five SSP marker scenarios for the baseline (left column), RCP4.5 (middle column) and RCP2.6 (right column) cases. Colored lines indicate the marker model results for each SSP. Colored bars indicate the range of data in 2100 across all marker and non-marker projections for each SSP (models are depicted by icon). Grey line shows historical trends based on EDGAR data (Edgar 2015).

increases until 2060 (177 Mt CH₄) mainly due to livestock production for export in MAF and decrease strongly afterwards as global livestock demand decreases and agricultural management becomes more intensified. Similarly, N₂O emissions increase slightly until 2040 (3.5 Mt N₂O) and then decrease due to improved agricultural management systems with high nitrogen use efficiencies.

Baseline cumulative CO₂ emissions in 2100 are highest in SSP3 and lowest in SSP1 across all models (marker and non-marker). Emissions in SSP4 lie somewhere between SSP2 and SSP3 levels in both models, and emissions in SSP5 lie somewhere between SSP1 and SSP2 for most models (emissions in REMIND-MAGPIE are slightly above SSP2).

In the mitigation case RCP4.5, avoided deforestation strongly reduces CO₂ emissions in SSP5, SSP4 and SSP2 compared to the baseline scenarios. However, as a result of weak land use change regulation, CO₂ emissions from land use change still occur in SSP3 (307 Gt CO₂ cumulatively until 2100). In the RCP2.6 mitigation case, emissions are again higher in SSP4 and SSP5, due to displacement effects into pasture land caused by high bioenergy production combined with forest protection only (Popp et al., 2014), and (for SSP4) due to additional land demand for bioenergy crop production in low income regions like MAF and ASIA without forest protection. Afforestation increases terrestrial C sequestration especially in SSP2 in LAM, MAF and ASIA and in the high income regions (OECD, LAM and REF) of SSP4 where land use change is successfully regulated. CH₄ emissions in the mitigation cases are remarkably lower compared to the baseline cases in all SSPs due to improved agricultural management (such as improved water management in rice production, improved manure management by e.g. covering of storages or adoption of biogas plants, better herd management and better quality of livestock through breeding and improved feeding practices). Dietary shifts away from emissions-intensive livestock products (SSP2) also lead to decreased CH₄ emissions. N₂O emissions are significantly lower particularly in the RCP4.5 scenario due to improvement of N-efficiency and improved manure management. However, high levels of bioenergy production result in increased N₂O emissions in

SSP5 due to N fertilization of dedicated grassy bioenergy crops such as Miscanthus.

3.4. Food price dynamics

SSP-specific changes in population, income, international trade, agricultural expansion and technological change as discussed above are the major drivers for long-term changes in world food prices. For the baseline scenario, **SSP2**, **SSP4** and **SSP5** show either flat or slightly falling world market prices for crops and livestock products by 2100, compared to 2005 (Fig. 8). While average world market price effects are rather modest in these SSPs, there is more variation especially in SSP3 at the regional level. As access to international markets is limited in poor regions in SSP4, the highest price effects are projected for ASIA and MAF (Fig. S115). By contrast, **SSP1** shows global price decreases of about 60% by 2100 consistent with lowest demand for agricultural commodities, more rapid growth in agricultural productivity and globalized trade. The opposite is true for **SSP3**, where world market prices increase by about 50% as a result of large population increases, very low productivity increases, and restricted trade of agricultural commodities. Here, the highest price effects are projected for MAF and ASIA. The effect of different SSPs on global food prices is robust across marker and non-marker models, with most models showing higher food prices in SSP3 and lower prices in SSP1 in 2100 (AIM shows little difference in food prices between SSP1 and SSP2). Food prices in SSP4 and SSP5 are similar to SSP2, with small declines in SSP5 in GCAM & REMIND-MAGPIE and small increases in the AIM SSP4.

In the mitigation scenarios, particularly in RCP2.6, land based mitigation measures cause world market prices to increase relative to 2005 in the SSP2 (+110%), SSP5 (+170%) and SSP4 (+570%) scenarios as a result of the carbon tax, changes in agricultural management, increased bioenergy production, and land used for afforestation. As bioenergy production, forest mitigation activities, and the abatement of agricultural GHG emissions are limited in the SSP3 due to major implementation barriers, the food price is barely affected in RCP 4.5. In SSP1 mitigation does hardly influence food

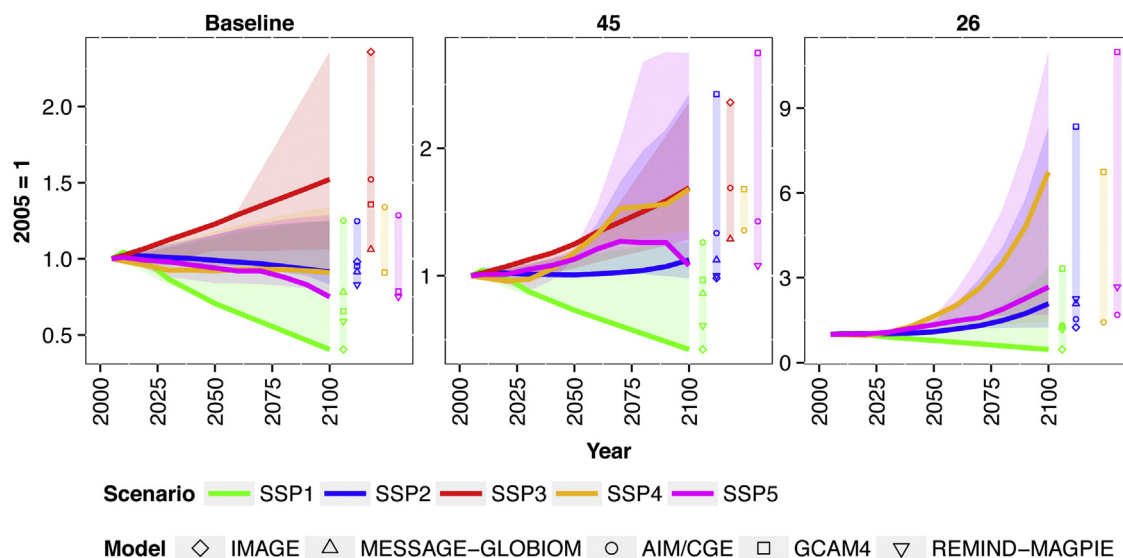


Fig. 8. Change in world market prices [2005 = 1] aggregated across all crop and livestock commodities of the five SSP marker scenarios for the baseline (left column), RCP4.5 (middle column) and RCP2.6 (right column) cases (Note that baseline, RCP4.5 and RCP2.6 have individual scales). Colored lines indicate the marker model results for each SSP. Colored bars indicate the range of data in 2100 across all marker and non-marker projections for each SSP (models are depicted by icon).

prices due to a general ‘food first’ policy, which can restrict agricultural expansion to avoid deforestation, but further only allows bio-energy on areas not needed for food and feed production. In general, considerable agricultural intensification (such as in SSP5), responses in agricultural trade (such as in SSP4 and SSP5), and changes in total production and consumption (such as in SSP2) have the capability to diminish food price reactions. The uncertainty across models for food prices is significant, with GCAM projecting much larger increases in the mitigation cases than other models. These price effects in GCAM are due to the strong dependence on afforestation and bioenergy as mitigation options, leading to significant land competition. Due to this uncertainty, the selection of marker models strongly influences the ranking of this variable, unlike previous results. For food prices in the mitigation cases, all models show food prices that are lower in the SSP1 and higher in SSP3 than the SSP2 in 2100. Food prices in SSP4 are less than (GCAM) or equal to (AIM) prices in SSP2. Food prices in the SSP5 are higher than the SSP2 in all models. While the qualitative ordering is robust across models, the magnitude of change differs significantly across models, with GCAM showing higher increases due to mitigation than any other model.

4. Conclusion

Future development of the agricultural system depends strongly on population dynamics and economic growth. But also other basic socio-economic conditions such as technological change in the crop and livestock sector (Havlík et al., 2013; Weindl et al., 2015), investment in agricultural technology (Robinson et al., 2014), dietary patterns and food demand (Smith et al., 2013; Popp et al., 2010; Stehfest et al., 2009), trade of agricultural goods (Schmitz et al., 2012; Verburg et al., 2009) and interactions with other sectors (e.g., the energy system via bioenergy demand) (Popp et al., 2013) strongly influence land-use dynamics, GHG emissions, potential of land-based mitigation and impacts. It is therefore of key importance to improve our understanding of the agricultural system and land use under different sets of future socio-economic settings, such as the newly developed Shared Socio-economic pathways. IAMs with distinctive land-use modules, like those applied in this exercise, are well-suited tools for doing so as these models represent interconnections between the land sector and a whole suite of human systems. In the previous sections, we have shown the land-use sector as simulated by the SSP marker models reflecting the general storylines of the SSPs and their positioning with respect to socio-economic challenges to mitigation.

All in all, the SSP marker scenarios provide a broad range of potential land-use futures. In the SSP baseline cases without climate change mitigation, global cropland (including bioenergy crops) increases between 2005 and 2100 by 130 mio ha in SSP1 on the low and by up to 753 mio ha in SSP3 on the high end. Pastureland shows even more divergence with global area increases of up to 380 mio in SSP4 at the high and decreases of 943 mio ha in SSP1 at the lower end. The inclusion of mitigation efforts, particularly those in the most ambitious mitigation scenarios of RCP 2.6, broaden the range of potential future agricultural area, as total cropland expands by up to 1413 mio ha until 2100 in SSP4 due to expansion of bioenergy cropland, and pastureland decreases until 2100 by up to 940 mio ha in SSP5. These outcomes are consistent with the range of estimates reported in the recent literature. The AgMIP model comparison of global economic land use models projects global cropland changes between – 75 and + 450 mio ha between 2005 and 2050 under constant climate (Schmitz et al., 2014). The FAO projects an increase of 69 million ha for the same time span (Alexandratos and Bruinsma, 2012). Smith et al. (Smith et al., 2010) provided a review

of studies on land-use projections of the past two decades, indicating a range between 90 and 470 million ha in 2050. For 2030, Lambin and Meyfroidt (Lambin and Meyfroidt, 2011) report projected cropland changes between 125 and 265 million ha. However, all of these assessments do not focus so much on the variability of future socio-economic drivers, they rather examine business-as-usual scenarios, or a limited variation in drivers, and do not include land-based mitigation, thus excluding several sources for diverging land-use futures. In the broader scenario literature (Nakicenovic and Swart, 2000; Carpenter and Pingali, 2005; Van Vuuren et al., 2011) projections for cropland range from a decrease of 140 mio ha to an increase of 1130 mio ha in 2100 compared to 2005, whereas pasture land ranges between increases of 217 mio ha and decreases of 1550 mio ha.

The SSP land dynamics have consequences for sustainable development. First, the highest losses of forest and other natural land is observed in SSP3, mainly in MAF and LAM. These losses could have consequences for biodiversity. In contrast, SSP1 shows abandonment of agricultural land and associated regrowth of natural vegetation in the baseline and mitigation cases. Similarly, long-term changes in food prices are affected very differently, with SSP1 indicating global price decreases whereas the opposite is true for SSP3 with highest price effects projected for countries of the Middle East and Africa as well as Asia. So in general, we see that the SSP1 has the most positive effects for sustainable development, with its sustainable food consumption (i.e. low food waste, diets with low shares of animal products), rapid growth in agricultural productivity and globalized trade.

But the wide range of possible land-use futures, both in literature and in this study, shows that there are major uncertainties in the global agricultural system, whose dynamics are still poorly understood.

Differences in land use projections result from a combination of different model architectures and philosophies, inherent uncertainties on modeled processes such as for example irrigation of cropland, and differences about how to parameterize these processes along various storylines such as the SSPs. While GDP and population trends were explicitly prescribed per SSP, spanning an uncertainty range across these dimensions, other important drivers were prescribed in qualitative terms (Table 2), and quantification was left to the model teams to cover the uncertainty of these drivers under a defined storyline (see table on IAM implementations in the SOM). In the interplay with different model structures and representation of processes across the IAMs, the final effect of such model drivers parameterization on agricultural production, trade, land use, GHG emissions and food prices introduces an additional level of uncertainty, and as a result, the range of outcomes across the multiple IAM realizations per SSP and RCP is rather wide. Individual behavior of marker and non-marker models, however, is similar for SSP1, SSP2, and SSP3 (see Fig SI16–SI19 and Tab SI1 in the SOM): Demand for agricultural products is lowest in SSP1 and highest in SSP3. Cropland area is lowest in SSP1 and highest in SSP3, leading to higher forest area in SSP1 and lower forest area in SSP3. Cumulative CO₂ emissions from land use change are lowest in SSP1 and highest in SSP3. Food prices are largest in SSP3 and smallest in SSP1. Models are less consistent with their representations of SSP4 and SSP5. Agricultural demand in SSP4 is less than (AIM) or equal to (GCAM) that of SSP2. Pastureland is significantly higher in SSP4 than in SSP2 in GCAM, but comparable in AIM. Agricultural demand in SSP5, however, is either lower or higher than SSP2 depending on the model. These differences do result in diverging cropland areas, but the differences between SSP5 and SSP2 are small in all models. Despite these differences, cumulative CO₂ emissions in the baseline scenarios represent the SSP storylines well, with SSP5 emissions falling between that of SSP1 and SSP2 and SSP4 emissions falling between

SSP2 and SSP3. While much of the discussion in this article focused on comparing among marker scenarios, the dependence on these marker scenarios does not affect the qualitative conclusions in most cases. That is, using a single model across SSPs would not change the ranking of scenarios in most cases. One notable exception is in the interpretation of food prices under a mitigation case. Here, model differences dominate scenario differences. Interestingly, the ranking within models is consistent, but the absolute values are strikingly different and mixing and matching models can be misleading.

One major uncertainty is the assumed increase in crop yields, which amounts at least to a doubling of current levels in most SSPs. While this would be a continuation of past trends, and is also in line with FAO's projections until 2050 (Alexandratos and Bruinsma, 2012), it is increasingly questioned whether past increases can be continued in the future for already high yielding crops and regions, as some important sources of yield improvements like increasing the harvested index, might have reached their limits. On the other hand, it is widely accepted that closing the yield gaps to currently attainable yields in low-income regions like Sub-Saharan Africa pose a huge potential for higher crop production (Mueller et al., 2012). With respect to the mitigation scenarios, there are several important uncertainties. For example, the large contribution of the land-use sector to climate change mitigation via delivering bio-energy and removing CO₂ from the atmosphere via BECCS relies on major innovations (significant yield increases, implementation of BECCS). Likewise, emission reduction of non-CO₂ gases in the agricultural sector rely on high adoption rates worldwide. Furthermore, some prominent land based mitigation options such as soil carbon management with an economic potential estimated at 3.5 GtCO₂eq per year by 2030 (Smith et al., 2013) are not included in this assessment. Finally, the IAMs only account for the emissions and carbon balance of land-based mitigation, while recent studies demonstrate the importance of land cover as well as land management changes (e.g. (Luyssaert et al., 2014)) and as a consequence that the inclusion of biophysical consequences of land-based mitigation within an IAM (Jones et al., 2015), could have significant consequences for climatic conditions at local and global levels. Another important caveat of our multi-model uncertainty analysis is that the uncertainty ranges for the individual SSPs are based on different sample sizes as not all modeling teams developed a scenario for each of the SSPs due to specific model characteristics (see Table 2 for an overview). For example SSP4, covered only by 2 IAMs, shows lowest uncertainty for most of the indicators compared to the other SSPs, especially in the cases without climate change mitigation. This fact complicates the assessment of scenario versus structural (model) uncertainty. Hence, in a next step, a much higher participation of additional IAM modeling teams in the quantification of the SSPs is needed wherefore the modeling protocol for this study has been made available to the broader IAM and land use modeling (e.g. AgMIP) community.

At present, SSP land use information is provided at the level of 5 world regions (<https://secure.iiasa.ac.at/web-apps/ene/SspDb>). However, information at much finer spatial resolution is needed, especially for climate model projections, impacts, vulnerability and adaptation assessments (Preston et al., 2011), for the assessment of gross land use changes with great importance for example for biodiversity assessments which are not visible at the regional scale and also for the assessment of sustainable development. This work is planned in subsequent phases of the scenario development. Additionally, these SSP outcomes will also be harmonized with the most recent data on historic land use, allowing for a smooth transition from the historical periods to the scenario period while conserving the original underlying IAM scenario signal, in a similar way as done for the RCPs (Hurt et al., 2011), but with an updated

methodology, more emphasis on land management, and a higher resolution of 0.25°.

The land-use futures of the SSPs, as elaborated by the five IAMs, shown in this study serve multiple purposes, and are expected to be used by a broad range of different communities. First, climate modeling is increasingly interested to study the multiple effects of land use and land-use change, including mitigation, on both biogeochemical and biophysical processes (Pitman et al., 2009), as land use change not only affects CO₂ concentrations (biogeochemical) but also albedo changes and evapotranspiration (biophysical) (Bonan, 2008; Jackson et al., 2008; Anderson et al., 2010). Previous efforts through the RCPs, resulting in a large number of experiments within the Coupled Model Intercomparison Project (CMIP5), were hampered by a lack of consistency across land-use trajectories, as the RCPs had been developed with a pure focus on radiative forcing targets in 2100 (Van Vuuren et al., 2011). The land-use information developed through the IAM implementation of the SSPs provide additional opportunities for assessment. For example, Earth System Models can better study the effects of deforestation and afforestation on climate by contrasting the land-cover dynamics in an SSP3 baseline scenario (deforestation) with those of an SSP1 RCP2.6 scenario (afforestation), an effort planned in the Land Use Model Intercomparison Project portion of CMIP6 (Lawrence et al., 2016). Second, in general the SSP framework is very well suited for climate change impacts, adaptation, and vulnerability (IAV) research, and in fact, it was designed to serve the needs of this community (Wilbanks and Ebi, 2013). The matrix architecture of combining SSPs with RCPs into new scenarios and comparing those with the respective baseline scenario without climate change impacts allows for a consistent assessment of climate change impacts under different socio-economic conditions, as well as vulnerability and adaptive capacity. In this study, climate change and CO₂ fertilization impacts are not considered on purpose, to allow a pure assessment of climate change mitigation pathways, without climate change and CO₂ fertilization impacts and adaptation already accounted for in the IAM scenario. In addition to assessing the single climate change and CO₂ fertilization impacts, the SSP framework can also be applied to investigate the combined effects of climate change and land-based mitigation in a next step. Third, the IAM SSP scenarios which focus on large-scale trends and therefore ignore dynamics within countries or regions, could be combined with regional integrated assessments. For example, the marker scenarios presented here could serve for example the AgMIP community by providing the global Representative Agricultural Pathways (RAPs) framing the regional scenario developments (Valdivia et al., 2015). Such regional and country-level integrated assessments and scenario developments are of great importance for developing concrete policy options towards sustainable development. In this, the link between global processes and regional drivers is an important consideration, and global results might serve as explicit boundary conditions for smaller scale assessments. However, this link remains a huge challenge due to the multiple feedbacks between the two scales. For example, the SSP scenarios delivered by the IAMs contain long-term projections of world market prices for agricultural commodities. Aggregate price indices at the global level reflect global drivers, such as production and consumption in major world regions as well as international trade (Nelson et al., 2014). But such aggregate results may neglect significant distributional consequences at the national and sub-national level, and therefore miss important impacts of future climate change as well as ambitious mitigation policies (Hussein et al., 2013).

Last but not least, the elaboration of the SSPs in the agricultural and land-use components of the IAMs has spurred activities of model comparison, harmonization and improvement, within and outside the IAM community. Most notably, it is carried further in

AgMIP's global agricultural economics team (Wiebe et al., 2015), and is being picked up by other global and regional assessments and research projects. But also for biodiversity and ecosystem services scenario assessments such as IPBES extended SSPs could be used as a starting point (Kok et al., 2016). In the end, these scientific communities working in a parallel and iterative process, as envisioned by the SSP design, will hopefully lead to a more complete understanding of land-use change dynamics at the global, regional and local scale, and its complex interactions with climate, impacts, adaptation and sustainable development.

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Appendix A. Supplementary data

Supplementary data associated with this article can be found, in the online version, at <http://dx.doi.org/10.1016/j.gloenvcha.2016.10.002>.

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