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Challenges of Global Agriculture in a Climate Change Context by 2050

AgCLIM50

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Title: Challenges of Global Agriculture in a Climate Change Context by 2050 (AgCLIM50)

Abstract
This report presents a global integrated assessment of the range of potential economic impacts of climate change and stringent mitigation measures in the agricultural sector. The analysis employs five global multi-region multi-commodity models and covers selected combinations of socioeconomic storylines and climate signals by mid-century. Model inputs are harmonised by using the same projections for population and GDP growth, as well as relative biophysical crop yield changes due to climate change. Model results can differ depending on model characteristics and the specific quantitative implementations of the socioeconomic storylines.

Contents

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Webpage with the results of the AgCLIM50 project

The dashboard with the results of the AgCLIM50 project is available on the following webpage: https://datam.jrc.ec.europa.eu

Executive summary

In the light of the Paris Agreement on Climate Change, the project "Challenges of Global Agriculture in a Climate Change Context by 2050" (AgCLIM50) assesses the impact of climate change on the agricultural sector by 2050, as well as the economic consequences of stringent global emission mitigation efforts under different socioeconomic and representative greenhouse gas concentration pathways. For this report a set of five global multi-region multi-commodity models are employed. Using different models and scenarios helps to explore a wide range of potential impacts, uncertainties, and the effects of data and methodological choices. Model inputs are harmonised by using the same projections for population and GDP growth, as well as relative biophysical crop yield changes due to climate change. Model results can differ depending on model characteristics and the specific quantitative implementations of the socioeconomic storylines.

Policy context

The Paris Agreement on Climate Change aims to keep the increase in global mean temperature well below 2°C above pre-industrial levels by the end of the century. The agricultural sector is, on the one hand, directly affected by climate change due to altered weather conditions and resulting biophysical effects. On the other hand, reductions in agricultural greenhouse gas emissions might be important to achieve the global climate change targets. In this context an integrated assessment of the range of potential impacts of climate change and stringent mitigation measures in the agricultural sector is required to provide insights for effective and efficient public and private sector decision making.

Key conclusions

The work presented in this report is a step forward in exploring the scenario space of the impact of future climate change scenarios on the agricultural sector. By trying to harmonise model assumptions (input side) rather than calibrating the models to produce similar results (output side), a wide spectrum of possible future scenarios is produced. More work needs to be done to clarify what causes different results across the models, as well as to identify the results that are robust across models despite very different implementation or policy mechanisms chosen by the various modelling teams. However, to achieve such a level of detailed analysis, further harmonisation of the input storylines is necessary, especially with respect to mitigation policies.

Main findings

Results of the study are relatively consistent across Shared Socioeconomic Pathways (SSP1, SSP2 and SSP3) and climate scenarios (RCP2.6 and RCP6.0 with and without mitigation policies in place), despite the fact of having models with some significant structural differences. The overall trends of the 12 scenarios are very similar and the few 'outliers' can be well explained by structural model characteristics or different scenario implementation choices. The main findings can be summarised as follows:

- Global agricultural production is lowest in SSP1 and highest in SSP3. This indicates that the demand for agricultural products is more influenced by the population developments and the assumptions on dietary preferences than by the GDP developments.
- The impact of climate change on agricultural production in 2050 is negative but relatively small at the aggregated global level. A surprising finding might be that the impact is fairly similar between RCP6.0 and RCP2.6. However, this is due to the selection of representative median scenarios as they actually imply rather similar yield impacts of the two RCPs in 2050. Conversely, as crop model results have shown, climate impacts will increasingly differ between RCP2.6 and RCP6.0 after 2050.

— Emission mitigation measures (i.e. carbon pricing) have a negative impact on primary agricultural production for all SSPs across all models.

— In terms of reduced global agricultural production, the impacts of mitigation policies are larger than the negative impacts due to climate change effects in 2050. However, this is partially debited to the limited impact of the climate change scenarios by 2050.

— Related to the production effects, climate impacts seem to affect global agricultural prices less strongly than ambitious mitigation policies across the models in this study. The price impact is higher in the livestock sector, because livestock production is more emission intensive and higher emission taxes directly increase livestock production costs.

— The magnitude of the producer price changes is very different between the models, which still requires a deeper analysis, but it seems mainly due to differences in the general model set-up (especially treatment of technological change) and assumptions on mitigation measures (e.g. carbon pricing).

— While all models largely agreed to the broad SSP and mitigation storylines, the specific implementation is not homogeneous across models, so that more work needs be done to increase consistency for a better comparison of model results. Moreover, results are only analysed at the global level, so that a regional 'zooming' would probably add valuable information to the study.

Related and future JRC work

The Economics of Agriculture Unit of the Directorate Sustainable Resources of the JRC is involved in several other projects related to the assessment of adaptation and mitigation of climate change in the agricultural sector, such as AgMIP (Agricultural Model Intercomparison and Improvement Project), PESETA (Projection of Economic impacts of climate change in Sectors of the European Union based on bottom-up Analysis) and EcAMPA (Economic assessment of GHG mitigation policy options for EU agriculture).

Quick guide

In this report the global impacts of climate change and stringent emission mitigation efforts on agricultural production, prices, trade, consumption, and the potential for emission mitigation/adaptation strategies is analysed. The analysis covers selected combinations of Shared Socioeconomic Pathways (SSP1/SSP2/SSP3) and Representative Concentration Pathways (RCP2.6/RCP6.0), employing five different models. Using a combination of integrated assessment (IMAGE), partial equilibrium (CAPRI, GLOBIOM, MAgPIE) and computable general equilibrium (MAGNET) models for the analysis ensures a good coverage of biophysical features on land availability, quality, and spatial heterogeneity, as well as cross-sectorial linkages through factor markets and substitution effects. The spectrum of results provides insights into potential impacts of climate change and greenhouse gas mitigation, related uncertainties, and how the modelling results are affected by data and methodological choices.

1 Introduction

In the light of the Paris Agreement on Climate Change at the 21st Conference of the Parties of the United Nations Framework Convention on Climate Change (UNFCCC), the European Commission's Joint Research Centre initiated the project "Challenges of Global Agriculture in a Climate Change Context by 2050" (AgCLIM50) to have a closer look at the range of potential economic impacts of climate change and mitigation options in the agricultural sector by 2050.

This report presents a set of alternative scenarios by different models, harmonized with respect to basic model assumptions, to assess the impact of climate change on the agricultural sector by 2050, as well as the economic consequences of stringent global emission mitigation efforts to stabilize global warming at 2°C by the end of the century under different Shared Socioeconomic Pathways (SSPs).

More specifically, in this report an analysis of the global impacts of climate change on agricultural production, prices, trade, consumption, and the potential for emission mitigation/adaptation strategies is conducted. For this purpose, the analysis covers selected combinations of SSPs and Representative Concentration Pathways (RCP)[1]. The main drivers behind SSPs are based on the recent work done by the Integrated Assessment Modelling Consortium (IAMC) for the Fifth Assessment Report (AR5) of the IPCC (2014).

The following five models have been used for the analysis:

- CAPRI: Common Agricultural Policy Regionalised Impact Modelling System
- GLOBIOM: Global Biosphere Management Model
- IMAGE: Integrated Model to Assess the Global Environment
- MAGNET: Modular Applied GeNeral Equilibrium Tool
- MAgPIE: Model of Agricultural Production and its Impact on the Environment

Using a combination of integrated assessment (IMAGE), partial equilibrium (CAPRI, GLOBIOM, MAgPIE) and computable general equilibrium (MAGNET) models for this analysis ensures a good coverage of (a) biophysical features on land availability, quality, and spatial heterogeneity; and (b) cross-sectorial linkages through factor markets and substitution effects.

Scenarios are implemented for the projection year 2050 and have global coverage with disaggregation into major world regions. Results are analysed with a focus on global implications of climate change and related policies. The focus of the analysis is on major crop groups (wheat, coarse grains, rice, sugar, oilseeds) and livestock products (meat from monogastrics, beef and milk).

Model inputs are harmonized by using the same projections for population and GDP growth over time, but model results differ depending on the specific quantitative implementations of the SSP storylines. The effects of ambitious mitigation with residual climate impacts, while stabilizing global warming at 2°C, is also systematically compared. The scenario setting is outlined in Table 1, indicating also the adaptation challenge for agriculture within the different SSPs.

(1) RCPs were selected and defined by their total radiative forcing (i.e. cumulative measure of human emissions of GHG from all sources expressed in Watts per square meter).

Table 1. Scenario setting, including residual impacts and the adaptation dimension

	Climate	Focus	SSP1 'Sustainability'	SSP2 'Middle of the Road'	SSP3 'Fragmentation'
			Adaptation challenge: low	Adaptation challenge: medium	Adaptation challenge: high
A	NoCC	No climate change	SSP1_NoCC	SSP2_NoCC	SSP3_NoCC
B	RCP6.0*	Climate change impacts	SSP1_CC6	SSP2_CC6	SSP3_CC6
C	NoCC	Mitigation measures for 2°C stabilization without residual climate change impacts	SSP1_NoCC_m	SSP2_NoCC_m	SSP3_NoCC_m
D	RCP2.6*	Mitigation measures for 2°C stabilization + residual climate change impacts	SSP1_CC26_m	SSP2_CC26_m	SSP3_CC26_m

* Based on a scenario with median climate impacts (across different crop model/climate model combinations), without CO_2 fertilization

Scenarios in row A reflect baseline socioeconomic changes without climate change impacts (NoCC). Scenarios in row B reflect the median climate impacts (across different crop model/climate model combinations) from RCP6.0, without CO2 fertilization. Therefore, the pure effects of climate change on agriculture can be analysed by comparing scenarios in row A and B.

Scenarios in row C depict the pure effects of ambitious mitigation efforts on agriculture with no residual climate change impact. Scenarios in row D implement ambitious mitigation measures (e.g., bioenergy use, afforestation, reduction of methane and nitrous oxide emissions in agriculture) in order to stabilize global warming at 2°C above pre-industrial levels. As an additional challenge for the agricultural sector, the median climate change impacts from RCP2.6 without CO_2 fertilization are added. By systematically comparing results of the scenarios in row D (RCP2.6) to scenarios in row C (NoCC), the relative importance of mitigation effects and the residual climate impacts on agriculture at 2°C of warming will be assessed. The combination of mitigation efforts and residual climate impacts in the scenarios in row D are a key innovative element in a multi-model study compared to the existing scientific literature on mitigation (like e.g. Nelson et al. 2014; Lotze-Campen et al. 2014).

It is expected that model results for the same scenario will differ significantly due to different implementations of the qualitative SSP storylines in the participating models.

2 Key characteristics of the models

A total of five global multi-region multi-sector models were employed to run a set of well-defined scenarios for 2050. The set of models includes one computable general equilibrium (CGE) model, three partial equilibrium (PE) models and one integrated assessment model (see Table 2). Both the spatial resolution and the level of disaggregation of the agricultural sector are very different across these models – both are functions of each model's history and original purpose.

The employed models differ in a number of other characteristics, as shown in Table 2. For instance, some of the models can be used to model alternative levels of second-generation bioenergy production, while the other models either have no explicit representation of bioenergy or focus on feedstock use for first-generation biofuels, electricity and/or heating. The table also shows that the MAGNET CGE model, in line with most CGE models, has a spatially explicit representation of bilateral trade flows using the Armington approach. In general, most PE models consider only net-trade to a spot world market. The PE models used in this study are exemptions to this role as GLOBIOM (Enke-Samuelson-Takayama-Judge spatial equilibrium specification) and CAPRI (Armington specification) represent bilateral trade flows. The agricultural demand is endogenous in GLOBIOM, CAPRI and MAGNET by iso-elastic or CDE (constant differences of elasticities) demand functions and exogenous for MAgPIE.

The IMAGE model is a global integrated assessment model that covers the human and earth biospheres and gets its more detailed agricultural information by a linkage to the MAGNET model.

Brief descriptions of the individual models and references for detailed model descriptions can be found in the annex.

Table 2. Key characteristics of the participating models

Model	Institution	Type	Economy coverage	Agric. policies	Bioenergy	Agric. supply	Final demand	Trade
MAGNET	Wageningen Economic Research, The Netherlands	CGE	Full economy	Price wedges, quota (adjusted from GTAP)	Endogenous 1st generation (incl. biofuel targets)	Nested CES	CDE private demand* and Cobb-Douglas utility	Armington spatial equilibrium
GLOBIOM	IIASA, Austria	PE	Agriculture, Forestry, Bioenergy	Implicitly assumed unchanged	Exogenous demand from MESSAGE system model	Leontief	Iso-elastic*	Enke-Samuelson-Takayama-Judge spatial equilibrium
MAgPIE	PIK, Germany	PE	Agriculture, Bioenergy, Water	Implicitly assumed unchanged	Exogenous demand from energy system model	Leontief	Scenario-specific exogenous trends over time	Scenario-specific trends in regional self-sufficiency rates
CAPRI	University of Bonn, Germany	PE	Agriculture	Explicitly represented	Endogenous 1st generation calibrated to exogenous baseline	Regional agricultural nonlinear mathematical programming	Second order flexible Generalised Leontief indirect utility	Armington spatial equilibrium
IMAGE	PBL, The Netherlands	IAM	Linked to MAGNET	See MAGNET, plus agricultural GHG mitigation based MACC curves	Based on IMAGE energy model TIMER, 1st and 2nd generation	See MAGNET	See MAGNET	See MAGNET, plus energy trade in TIMER

Note: * Elasticities adjusted over time. See list of acronyms for full names.

3 Shared Socioeconomic Pathways and their implementation in the participating models

3.1 Background

Shared Socioeconomic Pathways (SSPs) were developed by the climate change research community to represent the socioeconomic dimension of the new climate scenarios (O'Neill et al. 2014; 2017). The SSPs contain narratives for future developments of demographics, economy and lifestyle, policies and institutions, technology, and environment and natural resources (O'Neill et al. 2017). Furthermore, the SSPs comprise quantitative projections of population and gross domestic product (GDP) at the country level (Crespo Cuaresma 2017; Dellink et al. 2017; KC and Lutz 2017; Leimbach et al. 2017). In this project we focus on three SSPs out of the total five: SSP1 (Sustainability) - featuring relatively high levels of economic growth, lower levels of demographic growth, high levels of education, international cooperation, fast technological growth, convergence between developed and developing countries, sustainability concerns in consumer behaviour…, SSP2 (Middle of the Road) - representing business as usual development, and SSP3 (Regional Rivalry/Fragmentation), featuring opposite tendencies to SSP1 – relatively slow economic growth, sustained population growth,… The positioning of these scenarios in the space of challenges for adaptation and mitigation is depicted in Figure 1.

Figure 1. The scenario space to be spanned by Shared Socioeconomic Pathways, differing in challenges for adaptation and for mitigation

Source: O'Neill et al. (2017)

The major variables and their semi-quantitative values which describe alternative future developments in the land use sector consistently with the general SSP narratives are summarized in Table 3. Four elements were considered: Land use change regulation, Land productivity growth, Environmental impact of food consumption, and International trade. Depending on the scenario and element, different trajectories were indicated for three country income groupings (Low, Medium, High).

Table 3. SSP elements for the land use sectors

SSP elements	SSP1			SSP2			SSP3		
	Country income groupings								
	Low	Med	High	Low	Med	High	Low	Med	High
Land use change regulation	strong			medium			weak		
Land productivity growth - *Crop yields* - *Tech. progress in livestock*	rapid	rapid	medium	medium			slow		
Environmental impact of food consumption - *Food demand* - *Losses and waste management*	low			medium			medium		
International trade	globalized			regionalized			regionalized		

Source: Popp et al. (2017)

Five Integrated Assessment Modelling (IAM) teams were involved over the past five years in developing the land use related storylines of the SSPs for implementation in their models: AIM/CGE (Fujimori et al. 2017), GCAM (Calvin et al. 2017), IMAGE-MAGNET (van Vuuren et al. 2017), MESSAGE-GLOBIOM (Fricko et al. 2017), and REMIND-MAgPIE (Kriegler et al. 2017). Three of these teams (MESSAGE-GLOBIOM, IMAGE-MAGNET, and REMIND-MAgPIE) have participated in the study at hand.

For the AgCLIM50 project is was decided to follow the same approach as the integrated assessment models in terms of exogenous drivers harmonization, using the same population (KC and Lutz 2017) and GDP (Dellink et al. 2017) projections (available for download on the IIASA webpage[2]), but for the parameters translating land use related narratives, each modelling team relied on its own interpretations.

In what follows, we briefly present the interpretation of the narratives by the participating teams along the SSP elements specified in Table 3. For this we rely on information provided in the SSP land use overview paper (Popp et al. 2017), the individual modelling teams papers in the same Global Environmental Change special issue on SSPs (GLOBIOM (Fricko et al. 2017), IMAGE-MAGNET (van Vuuren et al. 2017), REMIND-MAgPIE (Kriegler et al. 2017)), and on personal communication. A summary is provided in Annex C, adapted and complemented from Popp et al. (2017).

3.2 Land use change regulation

The land use change regulations considered here actually do not have a specific climate change policy target but are primarily aiming at a different goal, which is usually biodiversity protection. In most of the models, these regulations are represented through forest protection measures.

In GLOBIOM, protected areas are delineated in line with the IUCN Protected Areas Management Categories I and II (UNEP-WCMC and IUCN 2016), i.e. strict nature reserves, wilderness areas, and national parks, according to the World Database on Protected Areas (WDPA - www.protectedplanet.net). In SSP2, it is assumed that Aichi Biodiversity Target 11, aiming at enrolling 17% of terrestrial and inland water areas under protected areas (Convention on Biological Diversity 2011) is met and hence protected areas are increased by 50% by 2020. In SSP1, it is assumed that the world will

([2]) https://tntcat.iiasa.ac.at/SspDb

go even beyond the targets and the protected areas in Category I and II will triple. SSP3 assumes only the current level of protection.

IMAGE-MAGNET considers three land use regulation components:

— Forest protection: SSP2 achieves the Aichi target aiming at 17% of land in protected areas by 2050, SSP1 assumes Aichi target of 17 % plus additional prevention of agricultural expansion so that a total 34% of land is excluded from agricultural expansion, and finally SSP3 keeps the protected areas within the current extent.

— Deforestation: non-agricultural deforestation is eliminated in 2020, 2040 and 2060 in SSP1, SSP2 and SSP3, respectively.

— Urban area: expansion of built up area is a function of population growth and urbanization rates as projected for the individual SSPs by (Jiang and O'Neill 2017).

MAgPIE represents forest protection based on the data on area of forest in protected areas in the Global Forest Resources Assessment (FAO 2010). The protected areas which in 2010 covered about 12.5% of the forests, remain the same in SSP3, increase by 50% until 2100 in SSP2, and increase by factor 4 in SSP1.

In CAPRI, improved forest protection is simulated through a carbon price of 5 EUR/t of non-CO_2 emissions in agriculture (i.e. methane and nitrous oxide) and in the LULUCF sector[3] in SSP1 and 2.5 EUR/t in SSP2. This carbon price indirectly produces a shift in the use of land from agriculture to other land classes, such as forestry.

3.3 Land and livestock productivity

The land productivity element covers crop and livestock productivity developments.

3.3.1 Crop yields

Crop yield growth may be represented as input neutral. However, some models consider also the relation between yield growth and variable inputs (e.g. use of fertilizers and pesticides). Moreover, most of the economic models have an exogenous and an endogenous component of yield developments, the latter one triggered by changes in relative prices.

For GLOBIOM, future crop yields were projected based on econometric estimation taking into account the long-term relationship between crop yields and GDP per capita.[4] The yield projections showed then an average annual increase of 0.66% in the global South for SSP1, 0.60% for SSP2, and 0.35% for SSP3. The elasticity of variable inputs use, including fertilizers, with respect to the yield change was set to 0.75 for SSP1, 1.00 for SSP2, and 1.25 for SSP3.

IMAGE-MAGNET also projected crop yield increase as a function of GDP, leading to highest yields in SSP1 and lowest yields in SSP3 (for details see Doelman et al. forthcoming). Nitrogen use efficiency was calibrated to FAO projections for SSP2. For SSP1 and SSP3, 20% higher and 20% lower nitrogen use efficiencies are assumed respectively. Furthermore, irrigation water use efficiency was assumed to be highest in SSP1 and lowest in SSP3.

In MAgPIE, no exogenous crop yield growth component is considered. All the elements of yield growth are made endogenous and the decision to invest in yield improvements is based on cost competitiveness compared with land expansion (Dietrich et al. 2014). Scenario specific discount rates are used, from 4% in SSP1 up to 10% in SSP3, which

([3]) As the representation of the LULUCF sector is still incomplete for non-European regions in CAPRI, the LULUCF part was only effective in Europe, but indirect effects also ensured a curb on agricultural areas outside of Europe that was able to mimic forest protection.

([4]) Crop yields in levels from FAOSTAT were fitted on countries' logarithmized GDP per capita over the period 1980-2009 by fixed effects panel estimation. The coefficient for yield response to GDP per capita was informed by observations stemming from countries in the same economic group. Estimation was carried out for each of the 18 GLOBIOM crops separately.

modifies the costs of land expansion and intensification depending on the different quality of governance (Wang et al. 2016). Nitrogen uptake efficiency converges to 60% globally by 2050 under SSP2, and to 65% and 70% in 2050 and 2100 under SSP1. These calculations are based on (Bodirsky et al. 2014).

CAPRI has implemented 75% of the yield growth estimated for the three SSPs in GLOBIOM. The rationale is that about 25% of the yield growth is covered endogenously in the model. Furthermore, the carbon price mentioned in section 3.2 is implemented, leading as well to endogenous adjustments towards increased fertilizer use efficiency (i.e. the carbon price introduces a cost per emission unit of nitrous oxide, which in turn increases the cost of nitrogen fertilizer use and hence will lead to an increased fertilizer use efficiency).

3.3.2 Technological progress in livestock production

Livestock productivity is a more complex concept than crop yields. It depends on the amount of nutrients needed to produce a unit of output but also on the composition of the feed ratio, and finally the feed and forage yields in regions where they are produced. Most model teams focused here on the first dimension. Similar as for crop yields, feed conversion efficiency will be typically the result of an exgenous component, which can be associated for instance with genetic improvement/breeding, and an endogenous component related to livestock management.

In GLOBIOM, to determine the exogenous component of feed conversion efficiency, first, global historic annual rates of feed conversion efficiency increase were estimated for the individual livestock products from the AgRIPE (Agricultural Representative Pathways and Emissions) framework fit with FAOSTAT data (Soussana et al. 2012). For SSP2, the past global trends were expanded into the future respecting, however, biophysical ceilings. The regional and SSP specific annual rates of increase were then calculated by scaling the global SSP2 projections by the rates of change estimated for crop yields as described above. This resulted in an annual rate of change in the global South of 0.26% for SSP1, 0.24% for SSP2 and 0.14% for SSP3. Depending on the SSP, GLOBIOM allows for more or less important switches between the livestock production systems. Under SSP1, 5% of the livestock production systems can be converted to another productions system annually, for SSP2, it is only 2.5%, and for SSP3, the livestock production systems structure is frozen.

IMAGE-MAGNET uses for livestock productivity improvements in SSP2 directly the FAO projections, plus own expert judgement where no FAO information is available (e.g. on grazing intensities). Faster technological change occurs in SSP1, where the efficiency improvements reached under SSP2 in 2050 and 2100 are assumed to happen much earlier (2030 and 2050 respectively). Slower productivity growth in SSP3 is implemented in the IMAGE model by assuming that efficiency gains reached by 2050 under SSP2 are achieved only in 2100 in SSP3.

MAgPIE relies on expert information for its livestock productivity projections. It assumes strong intensification in developing regions and slow-down of intensification in developed regions for SSP1, and medium and slow intensification for SSP2 and SSP3, respectively.

In CAPRI, the carbon price described in section 3.2 applies also to direct emissions from livestock, such as methane from enteric fermentation, and thus leads to endogenous adjustments towards increased livestock production efficiency.

3.4 Environmental impact of food consumption

This element includes the developments in terms of dietary preferences, total per capita consumption, as well as losses and waste in the food supply chains. Scenarios are differentiated to provide drivers consistent with the environmental sustainability storylines of the SSPs. The market feedbacks are considered second order effects here.

3.4.1 Food demand

Total food demand is the result of population growth and per capita consumption. The per capita consumption and the structure of the diet is for most models a function of GDP per capita, prices and preferences.

In GLOBIOM, changes in GDP per capita determine demand variation depending on pre-calculated income elasticity values. Therefore, unlike in the case of prices, the income effect is endogenous to the model. Elasticities are, however, not constant and change over time reflecting the change in marginal utility associated to food consumption when a country progressively develops. To derive this parameter, we build first reference trajectories of the income elasticities mainly based on FAO projections (Alexandratos et al. 2006). The general rule for developed countries is that consumption does not exceed 3600 kcal/capita/day, which is slightly higher than the level of Western Europe. The only exception in GLOBIOM is the United States, showing already consumption over this level (about 3800 kcal/capita/day).

Assumptions were then adapted to match the diet storylines for the different SSPs as follows. For SSP2, the reference income elasticity trajectories are used. For SSP1, future diets are considered to be more sustainable than in the FAO baseline, both in terms of least developed regions faster improving the overall levels of consumption, and the developed world turning to less resource and carbon intensive products:

— First, to reflect the better management of domestic waste in developed countries, consumption per capita in these regions is assumed almost constant.

— Second, animal protein demand is reduced in regions where more than 75 g protein/capita/day are consumed for animal and vegetal products. A minimum consumption of 25 g protein/capita/day of animal calories is ensured, but red meat consumption is reduced to 5 g protein/capita/day (but the target remains possible through the consumption of non-ruminant meat, eggs and milk). For developing regions, more nutritious diets are assumed and this materialized through an increase in protein intake at 75 g protein/capita/day and a reduction of roots and tubers consumption at a level of 100 kcal/capita/day.

— Finally, for SSP3, the same set of elasticities is used as in SSP2 but since economic growth is much lower in developing regions, the income effects alone lead to a significantly lower demand growth per capita in these regions.

In IMAGE-MAGNET, the SSP2 food demand projections rely on the default demand system setup. In order to simulate the deviating dietary preferences in the alternative scenarios, a "taste factor" was introduced. Meat and dairy consumption is in the medium and high income regions projected under SSP1 20% and 30% below the SSP2 levels in 2050 and 2100, respectively. On the other hand, under the SSP3 scenario, meat and dairy demand is 20% and 30% above SSP2 levels in 2050 and 2100, respectively.

In MAgPIE, the dietary preferences are a function of GDP and time (Bodirsky et al. 2015). The default parameters are used for SSP2, however the minimum share of livestock products in the rich country diets is set to 15%. In SSP1, food demand per capita is capped at 3000 kcal per day assuming substantial reduction in household level waste.

In CAPRI, any excess of protein consumption from animal origin beyond 40 g/capita/day is reduced by 25% by 2030 and by 50% up to 2050 under SSP1. This is considered a moderate, but still feasible and non-negligible change in behaviour. As this rule mainly affects consumption in high income regions no exogenous compensation with higher intake of plant calories or protein was deemed necessary. SSP2 and SSP3 use the default model setup.

3.4.2 Losses and waste management

FAO (2011) specifies three types of losses (pre-distribution) according to the phase of the production chain in which they happen (production, post-harvest handling and storage, processing) and two types of waste sources (distribution/retail and consumption). However, losses at the production level and their future developments are implicitly covered in the yield projections. Moreover, waste at the consumption level is covered by food demand projections, which represent the actual intake plus the household level waste. Therefore, here we focus on the losses in the supply chain, starting with post-harvest handling and ending at the retail level.

In GLOBIOM, the percentage of the production lost or wasted is again a function of GDP. However, out of five commodity groups, only for two (oilseeds & pulses and milk) a meaningful relationship could be established. This was based on FAO (2011) data. For the other three commodity groups (cereals, roots & tubers, and meat) the share of losses and waste is kept constant across the SSPs.

IMAGE-MAGNET considers that in SSP2 losses and waste represent about 33% of the primary production. For SSP1 and SSP3, it is assumed that losses and waste will be reduced/increased by one third, reaching 22% and 44%, respectively. This reduction/increase is divided between agriculture, intermediate use in processing and final consumption.

MAgPIE and CAPRI do not apply any SSP specific setup regarding losses and waste management.

3.5 International trade

The participating models have very different ways of representing trade, from a spatial equilibrium approach, through domestic product preferences represented by Armington elasticities, to exogenous trading patterns. Therefore the international trade narrative has been translated to the individual models through very different mechanisms.

GLOBIOM represents trade costs as the sum of tariffs and transportation costs. In addition, expanding bilateral trade flows beyond the levels of the previous period creates an additional cost which increases with trade. This relationship is represented through an iso-elastic cost function. In SSP2, the default model setup is used. In SSP1, trade costs are reduced between countries, but intercontinental trade costs are increased to capture regional preferences. In SSP3, trade costs are increased for all international commodity flows.

IMAGE-MAGNET uses the default setup for SSP2 representation. In SSP 1, however, export subsidies and import tariffs are 50% reduced by 2020 and completely removed by 2030. An import tax is also included in SSP1 to represent the preference for local production. The tax is gradually growing until 2050 when it reaches 10% and is kept constant afterwards. The same tax also represents the food security concerns in SSP3.

In MAgPIE, there are two trade pools in the model, one with trade fixed to historical trade patterns, and another one with free trade according to comparative advantages. Reducing trade barriers is translated through increasing the share of the free trade pool (Schmitz et al. 2012). In SSP1, the trade barriers decline by 1% per year, which means that each year the share of demand traded in the free trade pool is increased by 1%. In SSP2, the share of the free trade pool increases by 0.5% per year, and in SSP3, there is no free trade pool.

CAPRI does not apply any SSP specific setup with regard to trade assumptions.

4 Climate Change Scenarios

4.1 Background

Climate change is projected to affect crop yields and grassland productivity across the globe. There is substantial variation and uncertainty in space and time, stemming from different climate signals, different climate models and different crop growth models. On top of that, there is substantial uncertainty on the effectiveness of the carbon dioxide (CO_2) fertilization on crop yields, which roots in the insufficient understanding of plants' response to CO_2 fertilization, especially in the long run. There is much evidence and little uncertainty, that CO_2 fertilization enhances photosynthesis in C3 plants (e.g. wheat and rice) but not in C4 plants (e.g. maize, sorghum and sugar cane)[5]. There is also evidence that CO_2 fertilization increases water use efficiency in all plants, but not necessarily leads to higher photosynthesis (Keenan et al. 2013). However, it is much less clear to what extent the enhanced photosynthesis actually translates into higher crop yields, as there are various plant physiological processes that respond to this, including down-regulation of photosynthesis, increased nutrient limitation, growth of plant organs other than the harvested storage organ (Leakey et al. 2009), higher susceptibility to herbivory (Zavala et al. 2008) or even the loss of desirable plant traits, such as the more favourable ratio between straw and grain in dwarf varieties that has been a major advance in breeding during the green revolution but which can be lost due to altered hormonal growth control under elevated CO_2 (Ribeiro et al. 2012). Consequently, future projections of crop yields under climate change and the associated elevated atmospheric CO_2 concentrations are typically conducted for two scenarios. One scenario assumes that the stimulation of photosynthesis can be translated into higher yields in the long term (fullCO2), the counterfactual scenario assumes that there is no long-term benefit of CO_2 fertilization (noCO2), which is typically implemented in models by running the models with constant CO_2 concentrations (see e.g. Rosenzweig et al. 2014).

4.2 Overview of available climate and crop model scenarios

This study comprises a representative selection of climate change impact scenarios on crop yields. The selection is based on multiple available combinations of results from Global Gridded Crop Growth Models (GGCMs), General Circulation Models (GCMs) and Representative Concentration Pathways (RCPs). For practical use, results from global gridded crop models are aggregated to the country level, as this was agreed among participating economic modelling groups as the common level of aggregation for further processing within the economic models.

Within the Inter-Sectoral Impact Model Intercomparison Project (ISI-MIP) fast-track data archive (Warszawski et al. 2014), data on climate change impacts on crop yields is available from seven global GGCMs (Rosenzweig et al. 2014) for 20 climate scenarios. The climate scenarios are bias-corrected implementations (Hempel et al. 2013) of the four RCP by five earth system or GCM from the Coupled Model Inter-comparison Project (CMIP5) data archive (Taylor et al. 2012), see Table 4.

([5]) C3 plants are the most common and the most efficient at photosynthesis in cool and wet climates. C4 plants are most efficient at photosynthesis in hot and sunny climates.

Table 4. GCM names and references from the ISI-MIP project which have been used to drive GGCM

GCM name*	Reference
HADGEM2-ES	Jones et al. 2011
IPSL-CM5A-LR	Dufresne et al. 2013
MIROC-ESM-CHEM	Watanabe et al. 2011
GFDL-ESM2M	Dunne et al. 2013a; Dunne et al. 2013b
NorESM1-M	Bentsen et al. 2013; Iversen et al. 2013

* See list of acronyms for full names

For this study, three GGCM have been selected based on data availability: EPIC (Williams 1995), LPJmL (Bondeau et al. 2007; Müller and Robertson 2014), pDSSAT (Jones et al. 2003; Elliott et al. 2014). Consequently, there are 15 scenarios available for each RCP. Note that EPIC did not submit any data for noCO_2 other than for all GCM for RCP8.5 and for HadGEM2-ES for all RCP. The selection of representative scenarios is therefore based on 15 GGCM x GCM combinations for RCP2.6 and 8.5 for the fullCO_2 assumption as well as for the RCP8.5 noCO_2 assumption. For all others (fullCO_2 assumption for RCP4.5 and 6.0 and noCO_2 assumptions for RCP2.6, 4.5 and 6.0), the selection is based on 11 GGCM x GCM combinations (see Table 5).

Table 5. Data availability for the 3 GGCM, 4 RCP and 5 GCM

GGCM*	Full CO_2 fertilization (fullCO_2)				No CO_2 fertilization (noCO_2)			
	RCP2.6	RCP4.5	RCP6.0	RCP8.5	RCP2.6	RCP4.5	RCP6.0	RCP8.5
EPIC	14 crops, grassland, 5 GCM	14 crops, grassland, 1 GCM (HadGEM2-ES)	14 crops, grassland, 1 GCM (HadGEM2-ES)	14 crops, grassland, 5 GCM	4 crops, 1 GCM (HadGEM2-ES)	4 crops, 1 GCM (HadGEM2-ES)	4 crops, 1 GCM (HadGEM2-ES)	14 crops, grassland, HadGEM2-ES, 4 crops for the other 4 GCM
LPJmL	12 crops, grassland, 5 GCM							
pDSSAT	4 crops, 5 GCM							

* See list of acronyms for full names
Source: EPIC (Williams 1995), LPJmL (Bondeau et al. 2007; Müller and Robertson 2014), pDSSAT (Jones et al. 2003; Elliott et al. 2014)

The assumption of inefficient CO_2 fertilization on crop yields is not covered to the same extent in the ISI-MIP fast-track archive. Data are available for LPJmL and pDSSAT for all combinations, but for EPIC data has only been submitted for all crops for HadGEM2-ES (Jones et al. 2011) for all RCP and for the other four GCM only the major 4 crops wheat, maize, rice and soybeans for RCP2.6 and 8.5. Consequently, scenarios assuming inefficient CO_2 fertilization effects on crop yields (noCO2) will have to concentrate on the extreme RCP with a different crop mapping or will have to focus on just one climate scenario.

The crop model simulations cover several crops which differ by GGCM from only 4 (pDSSAT) to 15 (EPIC). For the mapping of crops simulated in the GGCM to commodities used in the economic models, we apply the same mechanism as in Nelson et al. 2014, shown in Table 6. However, for the noCO2 scenarios, the missing crops may have to be supplemented from the GGCM-specific average of the other crops rather than by LPJmL (to avoid overly emphasis on LPJmL). Grassland yield simulations are available from LPJmL and EPIC, with the same constraints applying to EPIC data availability as for all crops other than the major four.

Table 6. Mapping of climate yield impacts from crops in the three crop models to the 24 IMPACT commodity classes

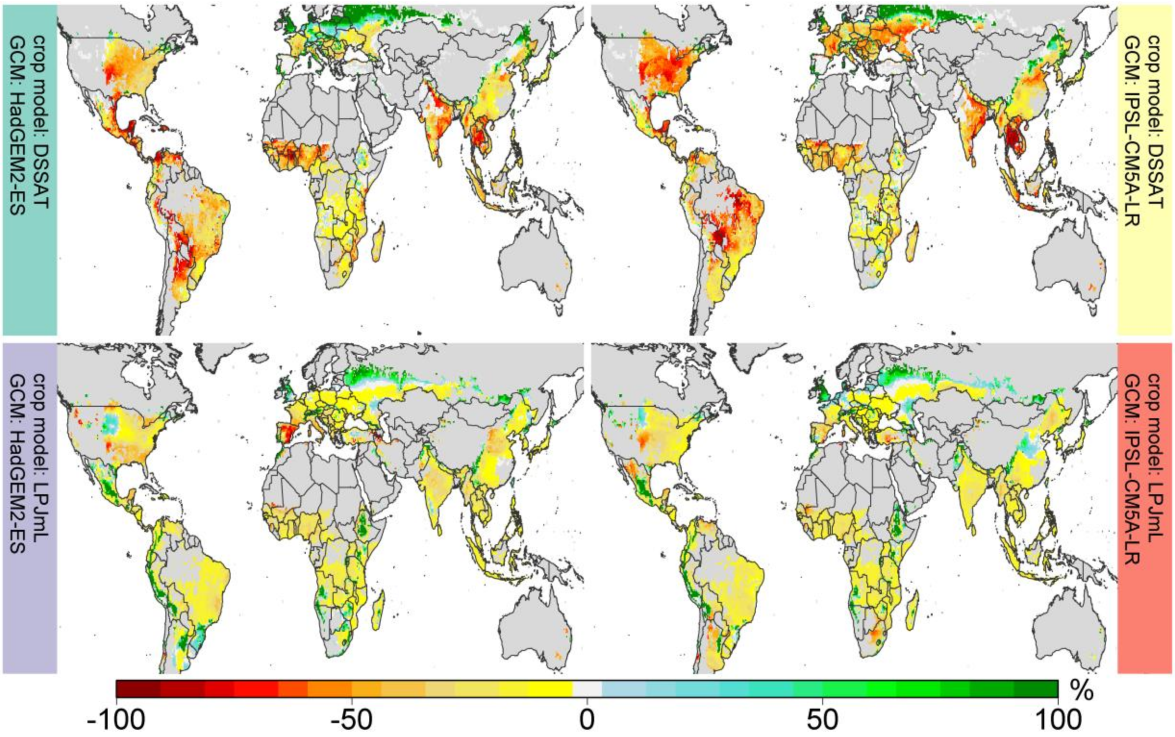
Agricultural commodity (acronym)	EPIC CO2 or HadGEM2-ES	EPIC noCO2 GCM other than HadGEM2-ES	LPJmL	pDSSAT
Maize (mai)	✓	✓	✓	✓
Millet (mil)	Sorghum	*	✓	*
Rice (ric)	✓	✓	✓	✓
Sorghum (sor)	✓	*	Millet	*
Wheat (whe)	✓	✓	✓	✓
Other grains (ogr)	Wheat**	Wheat**	Wheat**	Wheat**
Palm kernels (pak)	Sunflower	*	Sunflower	*
Rapeseed (rap)	✓	*	✓	*
Soybeans (soy)	✓	✓	✓	✓
Sunflower (sun)	✓	*	✓	*
Other oilseeds (ooi)	✓	*	✓	*
Cassava (cas)	✓	*	✓	*
Chickpeas (cpe)	Ground nuts**	*	Ground nuts**	*
Cotton (cot)	*	*	*	*
Ground nuts (nut)	✓	*	✓	*
Pigeon peas (ppe)	Ground nuts**	*	Ground nuts**	*
Potatoes (pot)	*	*	*	*
Sub-tropical fruit (stf)	*	*	*	*
Sugar beet (sgb)	*	*	✓	*
Sugar cane (sug)	✓	*	✓	*
Sweet potatoes (spo)	*	*	*	*
Temperate fruit (tef)	*	*	*	*
Vegetables (veg)	*	*	*	*
Other crops (ocr)	*	*	*	*
Managed grassland (mgr)	✓	***	✓	****

✓ Commodity class is directly represented by that crop (e.g. wheat is based on wheat simulations)
* Average of rice, wheat, and soybeans
** Only half of negative impacts are applied, representative of improved drought tolerance
*** Yield impacts taken from LPJmL
**** Yield impacts as average of EPIC and LPJmL if available, otherwise of LPJmL
Source: Modified from Nelson et al. (2014)

4.3 Selection of representative climate impact scenarios

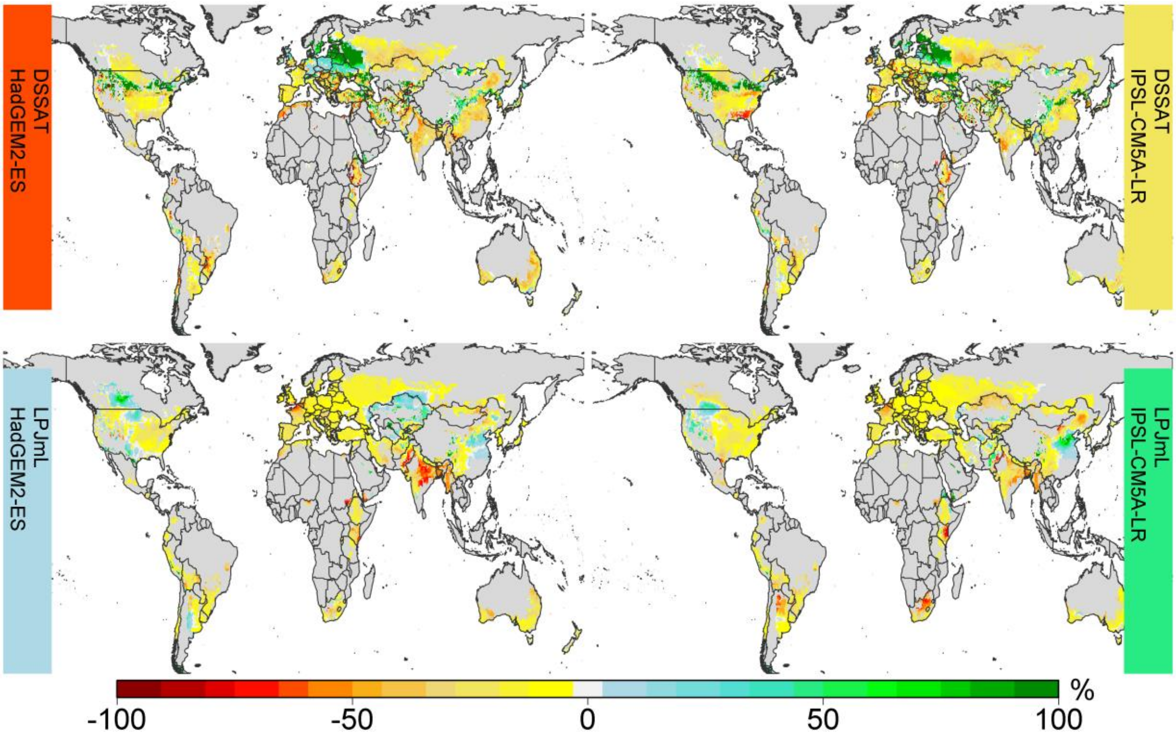
For the GGCM simulations with assumed full effectiveness of CO_2 fertilization on crop yields, the available data set allows for selection from 15 scenarios per RCP for the three selected crop models EPIC, LPJmL and pDSSAT (5 GCM x 3 GGCM). As this is still a large set of scenarios, we applied a statistical aggregation in order to reduce the number of biophysical yield shock scenarios for the global economic models. Given the spatial heterogeneity of impact projections, the spatial disaggregation (i.e. selection of analysis at pixel or regional level), the selection of average or median results for the consideration of a specific projection (e.g. optimistic or pessimistic), may lead to an overlap of extreme scenarios, as scenarios typically have some regions with positive and others with negative impacts. The sampling of the worst/best case in each pixel/region would thus neglect that negatively affected regions are typically partially compensated for by positively affected regions (see Figure 2 and Figure 3 as examples).

Figure 2. Differences in spatial patterns in rainfed maize (as projected by two GGCMs for two GCM for RCP8.5, assuming no effectiveness of CO_2 fertilization on crop yields)



Source: Modified from Müller and Robertson (2014)

Figure 3. Differences in spatial patterns in rainfed wheat (as projected by two GGCM for two GCM for RCP8.5, assuming no effectiveness of CO2 fertilization on crop yields)



Source: Modified from Müller and Robertson (2014)

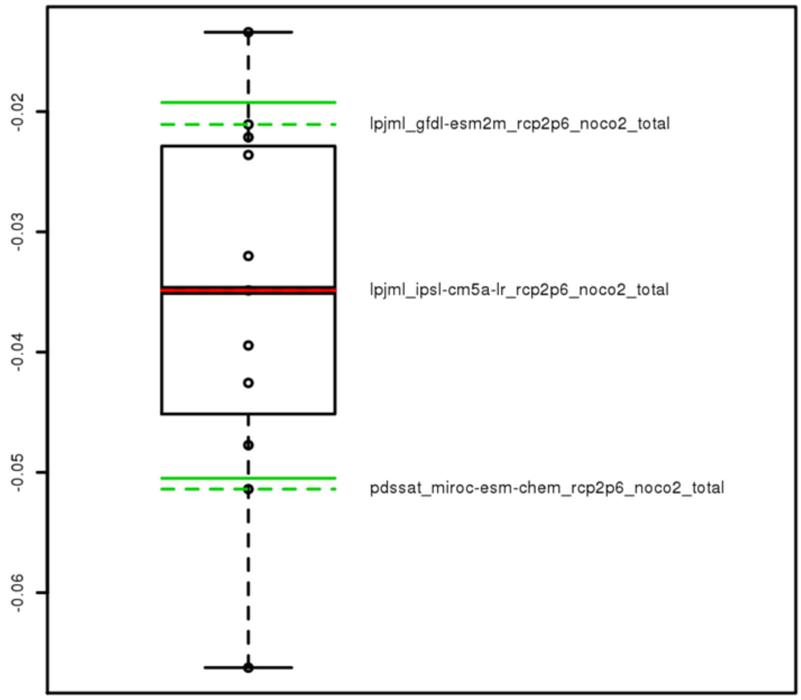
We assess climate change projections for different crops at the global level by aggregating current crop- and irrigation system specific areas based on the Spatial Production Allocation Model (SPAM) data base (You et al. 2010). The SPAM database does not include managed grassland, so that areas for these were extracted from Fader et al. (2010). The aggregation follows equation (1), where t is the time index (years), c is the crop index, p is the pixel index, i is the irrigation setting index (irrigated or rainfed), $prod_t$ is the total agricultural production of year t in calories, $area_p$ is the area of the pixel p in ha, $frac_{p,c,i}$ is the fraction of pixel p that is used for crop c with the irrigation system i, cal_c is the caloric density of crop c in cal/t and $y_{t,p,c,i}$ is the crop yield of year t in pixel p for crop c with the irrigation system i, n is the maximum number of elements of p, c, i:

$$prod_t = \sum_{p=1,c=1,i=1}^{n} (area_p * frac_{p,c,i} * cal_c * y_{t,p,c,i}) \qquad (1)$$

From the 15 GGCM x GCM combinations we used three explicit scenarios: one that represents the global median impact, and two that are closest to the median (+/- one standard deviation, SD) at the global aggregation. For this, we selected one GGCM x GCM combination for each RCP and each assumption on CO_2 fertilization that is closest to the median, the median +1 SD and the median -1 SD. This avoids the extreme bias of selecting pixel- or region-based values from that unit's impact distribution and keeps spatial consistency in impacts while still representing the median and one high- and one low-end scenario. In this exercise, the focus was on two different emission pathways (RCP6.0 and RPC2.6) and only the median cases were selected for further analysis in the economic models. For RCP2.6 the median scenario is represented by the combination of the GCM IPSL-CM5A-LR (Dufresne et al. 2013) and the GGCM LPJmL (Bondeau et al. 2007), see Figure 4, whereas the median scenario for RCP6.0 is represented by the combination of the GCM HadGEM2-ES (Jones et al. 2011) and the GGCM pDSSAT (Elliott et al. 2014), see Figure 5.

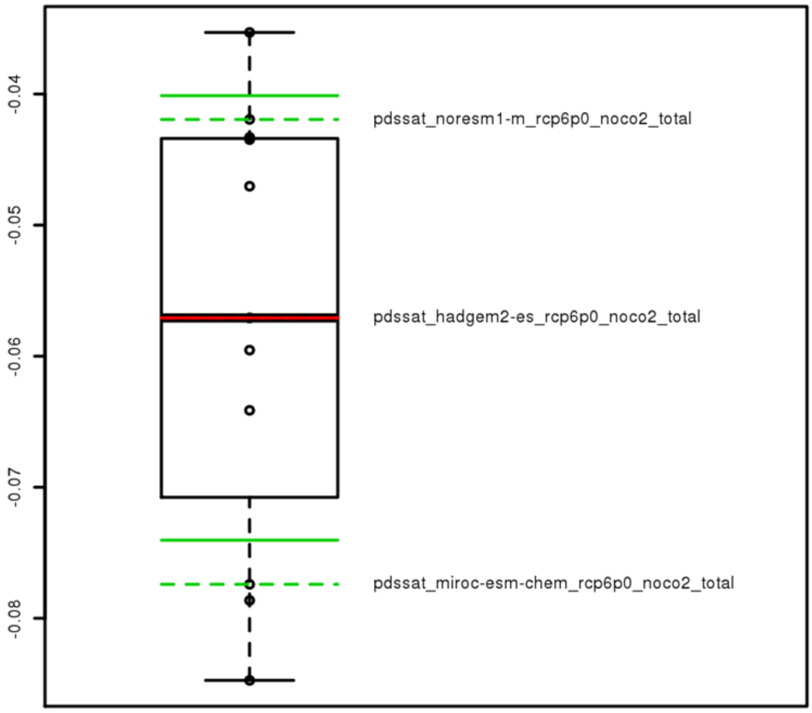
It has to be noted that RCP2.6 and RCP6.0 have been selected for their representativeness at the end of the 21st century (van Vuuren et al. 2011) and that they are not distinctively different in 2050 (the horizon of analysis in this study). In fact, in 2050, GHG concentrations of RCP2.6 are still close to peak concentration levels whereas RCP6.0 has still lower GHG concentrations in 2050 than RCP4.5, and the radiative forcing of RCP2.6 and RCP6.0 are quite similar in 2050. The main difference between these scenarios may thus be caused by the choice of the GCM (i.e. spatial patterns of climate change and spatial overlap of regions with more adverse conditions and cropping areas) and GGCM (i.e. different assumptions on crop management systems) (see Table 7).

Figure 4. Climate-induced changes in annualized growth rate of global calorie production: Spread and selection of three representative cases for RCP2.6 (assuming no CO_2 fertilization)



Note: Spread and selection of three representative cases for the RCP2.6 assuming no CO_2 fertilization; median in red, +/-1 SD in green; dashed lines indicate the representative GGCM/GCM combinations. Boxes span the interquartile range of the impact distribution; whiskers extend to the most distant data point within 1.5 times the interquartile range, which is in this case the full range. Annual growth rates

Figure 5. Climate-induced changes in annualized growth rate of global calorie production: Spread and selection of three representative cases for RCP6.0 (assuming no CO_2 fertilization)



Note: Spread and selection of three representative cases for the RCP6.0 assuming no CO_2 fertilization; median in red, +/-1 SD in green; dashed lines indicate the representative GGCM/GCM combinations. Boxes span the interquartile range of the impact distribution; whiskers extend to the most distant data point within 1.5 times the interquartile range, which is in this case the full range.

Table 7. Regionally aggregated climate change impacts (annual growth rates from 2000-2050) for wheat, maize, rice and soybeans

Region	Wheat		Maize		Rice		Soybeans	
	RCP2.6	RCP6.0	RCP2.6	RCP6.0	RCP2.6	RCP6.0	RCP2.6	RCP6.0
EUR	-0.0019	0.0006	-0.0002	-0.0012	-0.0002	-0.0005	-0.0003	-0.0032
FSU	-0.0002	-0.0027	-0.0006	-0.0003	0.0023	0.0005	-0.0001	0.0021
MEN	-0.0010	-0.0004	-0.0003	-0.0023	0.0000	-0.0005	-0.0006	-0.0036
SSA	-0.0018	-0.0045	0.0001	-0.0013	-0.0022	-0.0003	-0.0037	-0.0017
ANZ	-0.0016	-0.0024	0.0001	-0.0005	-0.0023	0.0006	-0.0025	-0.0002
CHN	0.0002	-0.0023	-0.0006	-0.0015	0.0004	0.0001	-0.0012	-0.0001
IND	-0.0009	-0.0023	-0.0011	-0.0023	-0.0013	-0.0022	-0.0025	0.0005
SEA	-0.0001	0.0029	-0.0014	-0.0020	-0.0014	-0.0006	-0.0017	0.0000
OAS	-0.0011	-0.0039	-0.0011	-0.0021	-0.0012	-0.0026	-0.0020	-0.0019
OSA	-0.0012	-0.0014	0.0011	-0.0016	-0.0013	-0.0002	-0.0042	-0.0006
BRA	-0.0018	-0.0026	-0.0005	-0.0033	-0.0018	-0.0020	-0.0037	-0.0030
CAN	-0.0003	0.0007	-0.0011	-0.0006	na	na	-0.0009	0.0015
USA	-0.0007	-0.0007	-0.0004	0.0004	-0.0012	-0.0007	-0.0001	-0.0001
GLO	-0.0008	-0.0013	-0.0003	-0.0008	-0.0009	-0.0009	-0.0021	-0.0009

Note: na = not applicable. EUR = Europe (excl. Turkey), FSU = Former Soviet Union (European and Asian), MEN = Middle-East / North Africa (incl. Turkey), SSA = Sub-Saharan Africa, ANZ = Australia/New Zealand, CHN = China, IND = India, SEA = South-East Asia (incl. Japan, Taiwan), OAS = Other Asia (incl. Other Oceania), OSA = Other South, Central America & Caribbean (incl. Mexico), BRA = Brazil, CAN = Canada, USA = United States of America, GLO = Global

The small differences in radiative forcing between RCP2.6 and RCP6.0 in 2050 put stronger weight on the spatial patterns of climate change impacts as simulated by GCM and the crop management assumptions in GGCM. As a consequence, for specific crops and regions climate change impacts can be less severe or more positive under RCP6.0 than under RCP2.6 (see Table 7). Moreover, mitigating climate change is not always positive for agriculture, especially in currently cooler regions or when climate change impacts are (over-)compensated by positive effects of CO_2 fertilization (Müller et al. 2015; Müller and Robertson 2014). In the interpretation of the results it is therefore important to note that regional responses of climate change impacts can be counter-intuitive with larger/more negative impacts under RCP2.6 (Figure 6) than under RCP6.0 (Figure 7) even when CO_2 fertilization is ignored here.

Figure 6. Regional climate change impacts for RCP2.6 as represented by the GCM IPSL-CM5A-LR and the GGCM LPJmL (national annual growth rates for the four major crops)

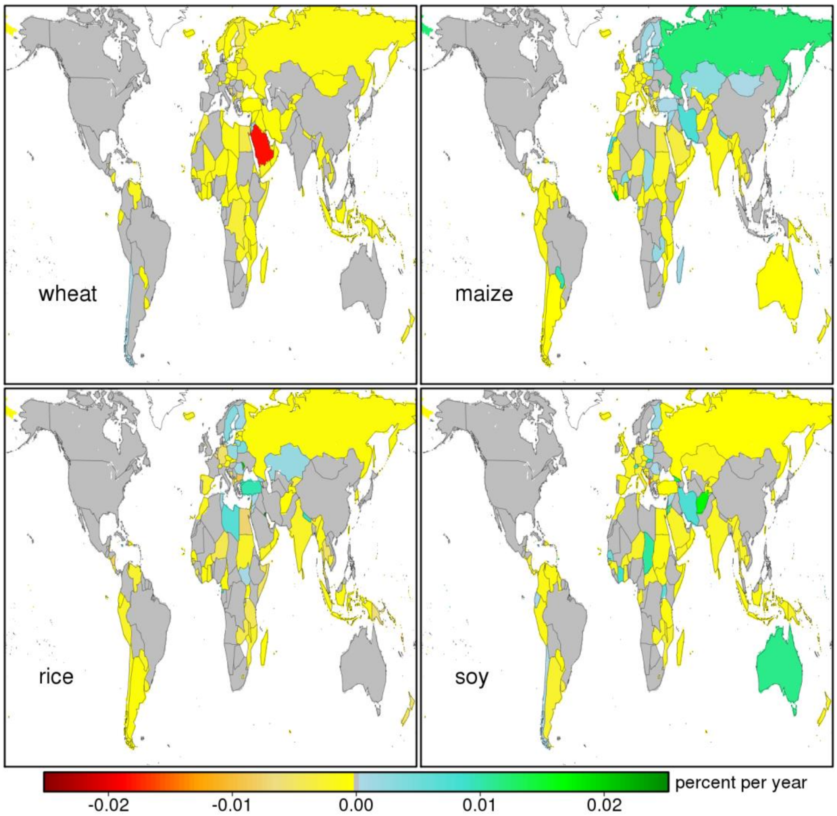
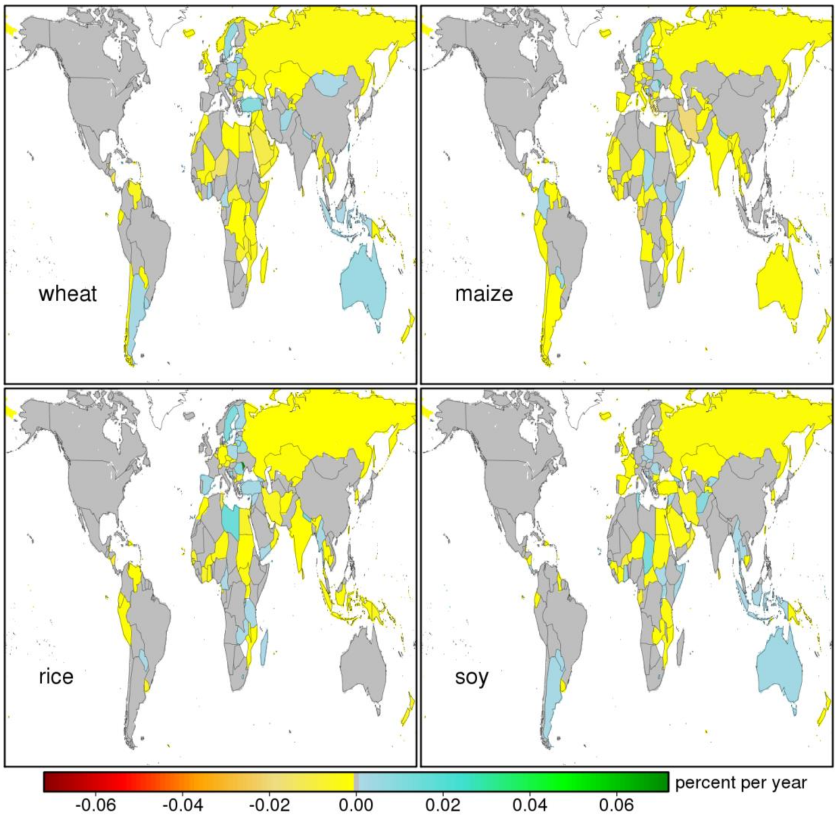


Figure 7: Regional climate change impacts for RCP6.0 as represented by the GCM HadGEM2-ES and the GGCM pDSSAT (national annual growth rates for the four major crops)



4.4 Databases

Variations in yields are supplied by GGCM as annualized growth rates from 2000 (1986-2015 average) to 2050 (2036-2065) at the country level. For EPIC the baseline is 1981-2010, as EPIC supplied data in 30-year time slices that all show strong trends over time within these packages. As such, only averages of 30 years within such simulation packages are employed here.

Data is supplied at country level for all four RCPs, the four major crops (wheat, maize, rice and soybean), managed grassland, as well as changes in total calories. Annual growth rates of crop yields are specified for the median case as well as the two cases representing plus and minus one standard deviation, as explained in section 4.3.

The selection of crop yield projections is independent of any socioeconomic setting. As such, any of the crop yield projections can be combined with different SSPs for developing future agricultural pathways.

5 Mitigation

5.1 Introduction

In order to achieve ambitious climate mitigation targets, both CO_2 and non-CO_2 GHG emissions need to be reduced substantially. Non-CO_2 emissions contribute about 30% to total global GHG emissions and to radiative forcing. While the abatement of non-CO_2 GHG emissions is initially relatively cheap compared to CO_2 emissions, there are limits to their abatement, and therefore the non-CO_2 mitigation share in total GHG emissions mitigation decreases in mitigation scenarios over time (Lucas et al. 2007). Understanding and quantifying the mitigation potential of non-CO_2 emissions and their uncertainties is crucial for estimating which climate targets can be achieved, and at which costs.

The most important non-CO_2 greenhouse gases are methane (CH_4) and nitrous oxide (N_2O), and agriculture is the largest contributor to these global anthropogenic non-CO_2 emissions. Agriculture's non-CO_2 emissions account for about 10-12% of total global GHG emissions. The most relevant sources of CH_4 emissions are enteric fermentation (32-40% of total agriculture emissions) and paddy rice cultivation (9-11%). The most relevant sources for N_2O emissions are related to livestock (37-77%, mostly from manure) and synthetic fertilizer application (12%) (Smith et al. 2014). This suggests that the agricultural sector may play a crucial role in climate change mitigation via methane and nitrous oxide abatement. However, the assessment of the reduction in agricultural emissions has received less attention compared to other land-based mitigation focusing on the carbon cycle such as bio-energy production, afforestation and reduced emissions from deforestation and forest degradation (REDD). Therefore, one of the objectives of the AgCLIM50 project is the assessment of agricultural non-CO_2 emission mitigation scenarios.

5.2 Mitigation scenarios

The focus of the mitigation scenarios within this study is on the mitigation of non-CO_2 emissions, because, as mentioned above, the mitigation of methane and nitrous oxide emission from the agricultural sector has received somewhat less attention than the land-based mitigation potential of CO_2 (e.g., bioenergy), extensively studied in other projects (like for example the Energy Modeling Forum[6]).

Extending beyond earlier studies with a focus on model comparison (Gernaat et al. 2015) and agricultural GHG mitigation potential (Herrero et al. 2016), we want to assess the following aspects:

- Medium- and long-term mitigation potential between the models and scenarios for the agricultural sectors.
- Mitigation strategies included in the models.
- Production, trade and price effects due to taxes on non-CO_2 emissions from agriculture (also indicating possible effects with regard to intensification, shifts in technologies and shifts across regions).
- Demand-side responses to taxes on non-CO_2 emissions from agriculture.

The assessment is carried out for SSP1, SSP2, and SSP3, with the corresponding mitigation scenarios aiming at a stabilization of climate change at 2°C with and without residual climate change impacts (see Table 8). The emission sources and mitigation measures covered in the models are presented in Annex B.

In the scenarios presented in Table 8, the column 'Mitigation' depicts the mitigation to achieve a certain climate target (note that this does not mean that climate change impacts are accounted for, as climate change impacts are specified in the RCP column). The purple colored cells indicate the GCM and GGCM used. Regarding the crop model

(6) See Energy Modeling Forum (EMF): https://emf.stanford.edu/

simulations, no effects from CO_2 fertilization are considered in the scenarios (i.e. the models are driven by fixed CO_2 concentration).

Table 8. Detailed description of scenarios

Scenario	**SSP**	**RCP**	**GCM**	**CO2Fertili**	**CropModel**	**Mitigation**
SSP1_NoCC	SSP1	presclim	NoCC	noco2	noCropModel	noMitig
SSP2_NoCC	SSP2	presclim	NoCC	noco2	noCropModel	noMitig
SSP3_NoCC	SSP3	presclim	NoCC	noco2	noCropModel	noMitig
SSP1_CC6	SSP1	RCP6.0	hadgem2	noco2	pdssat	noMitig
SSP2_CC6	SSP2	RCP6.0	hadgem3	noco2	pdssat	noMitig
SSP3_CC6	SSP3	RCP6.0	hadgem4	noco2	pdssat	noMitig
SSP1_NoCC_m	SSP1	presclim	NoCC	noco2	noCropModel	Mitig2degree
SSP2_NoCC_m	SSP2	presclim	NoCC	noco2	noCropModel	Mitig2degree
SSP3_NoCC_m	SSP3	presclim	NoCC	noco2	noCropModel	Mitig2degree*
SSP1_CC26_m	SSP1	RCP2.6	IPSL	noco2	LPJmL	Mitig2degree
SSP2_CC26_m	SSP2	RCP2.6	IPSL	noco2	LPJmL	Mitig2degree
SSP3_CC26_m	SSP3	RCP2.6	IPSL	noco2	LPJmL	Mitig2degree*

* If the 2°C target is not possible in the SSP3 related scenarios, the lowest possible target should be aimed for, and the forcing level should be reported. Mitigation: emission sources and mitigation measures covered in the models are presented in Annex B.

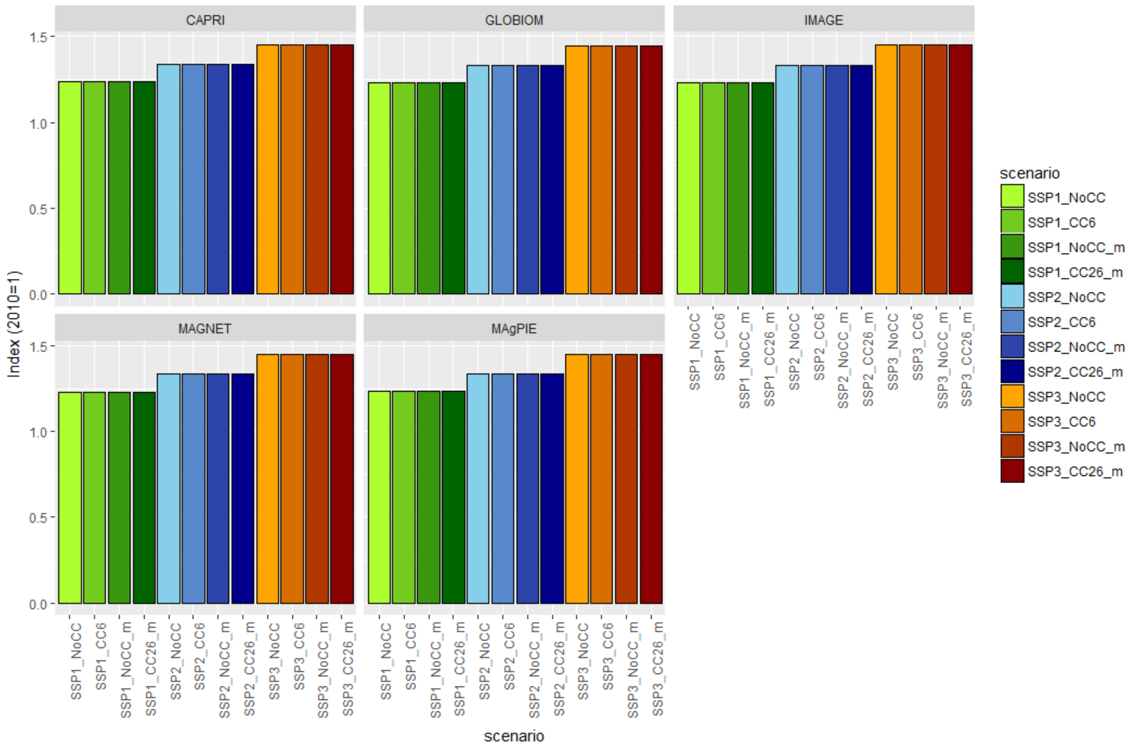
6 Results

In this section we present and discuss global scenario results with respect to the following variables: population, GDP, total agricultural production, production of ruminants and non-ruminants, land use (total, crops and livestock related), crop yields, producer prices (crops, livestock products), and emissions (CO_2 from land use, CH_4 and N_2O from agriculture). All results are presented as index changes for the projection year 2050 compared to 2010.

Results for SSP1, SSP2 and SSP3 are represented with green, blue and red bars, respectively. The first bar, within a certain colour, represents the no climate change scenario (NoCC) and the second bar from the left represents the same scenario with climate change (RCP6.0 climate forcing, CC6). The third bar, within a colour, represents the mitigation scenario without climate change (NoCC_m) and the fourth bar represents the same mitigation scenario with climate change (RCP2.6 climate forcing, CC26_m).

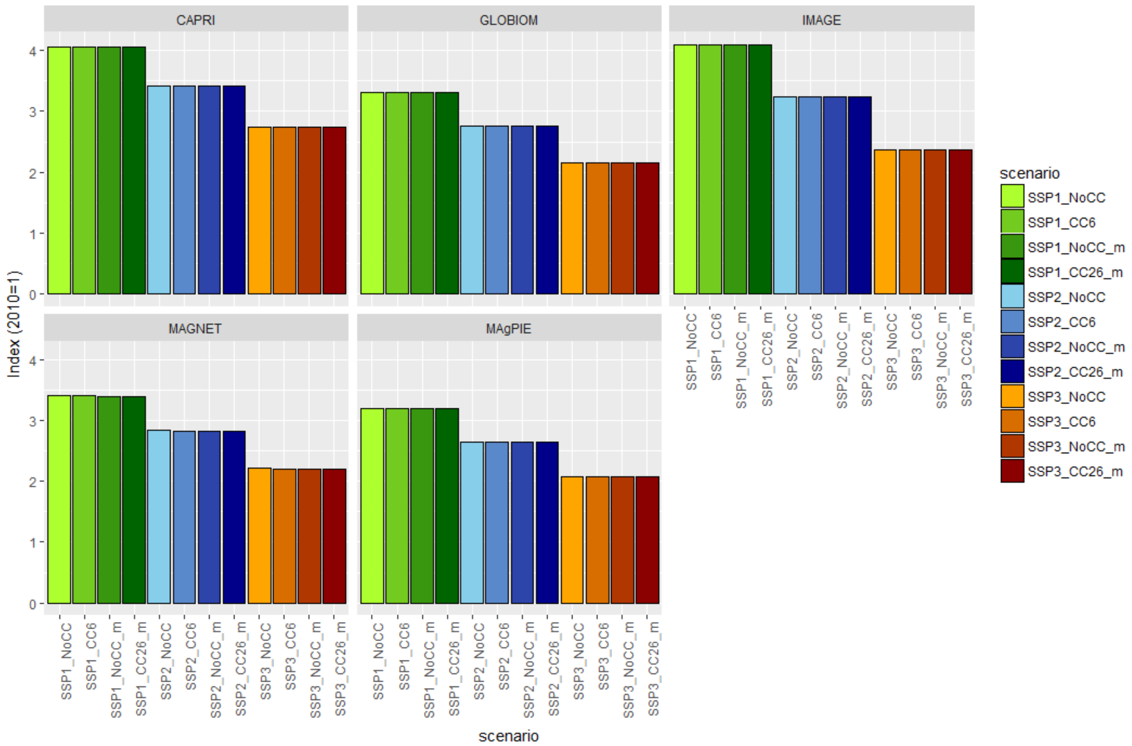
The impact of RCP6.0 climate forcing on agricultural production can be obtained by comparing the NoCC (first) and the CC6 (second) scenario within an SSP, and the impact of RCP2.6 climate forcing can be seen by comparing the NoCC_m (third) and the No_CC26_m (fourth) scenario. The impact of the mitigation measures compared to taking no mitigation action can be obtained by comparing the CC6 (second) and the CC26_m (fourth) scenario within an SSP.

Figure 8. Global population in 2050



Changes in population are an exogenous driver in all models included in this study. All follow the general SSP storyline, with lower population growth in SSP1 than in SSP2 and SSP3 (Figure 8). Population growth is assumed to be independent of the climate change and mitigation dimensions in scenarios.

Figure 9. Global GDP in 2050



GDP developments are exogenous in GLOBIOM, CAPRI, IMAGE and MAgPIE, and endogenous in MAGNET[7]. Absolute numbers are slightly different across models, as they have different methods to convert the GDP Purchasing Power Parity (PPP) to GDP Market Exchange Rate (MER), which is reported here[8]. However, the relative changes between SSPs are in line across models (Figure 9).

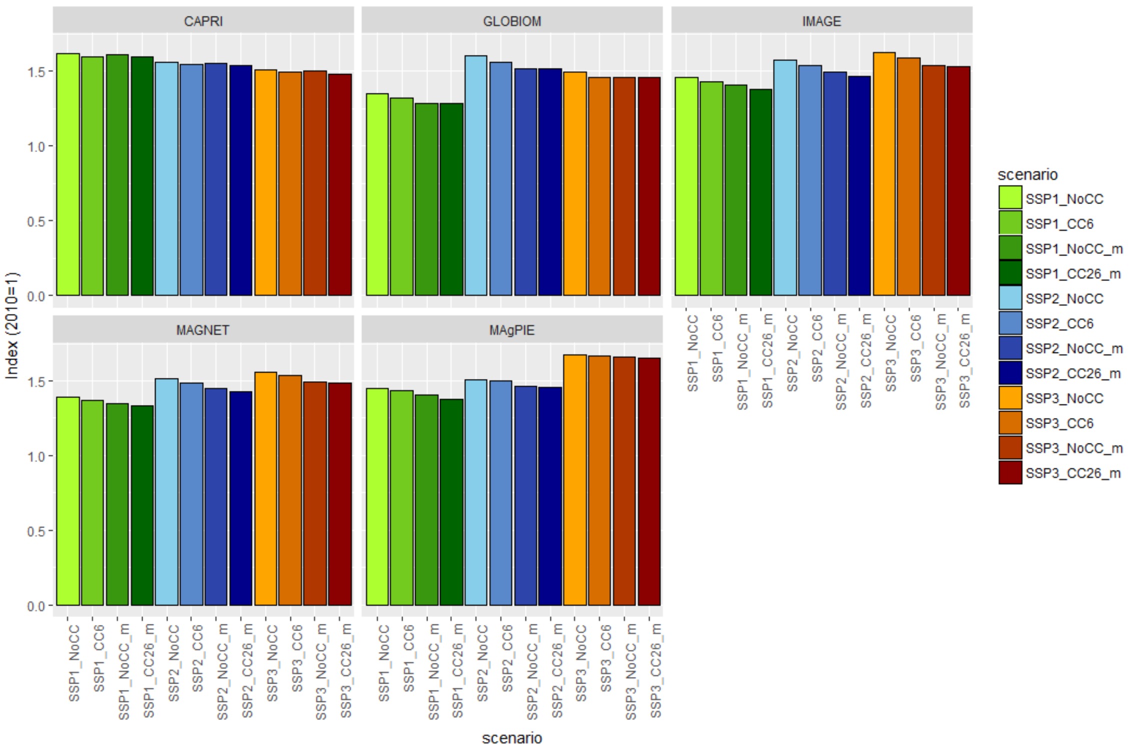
The SSP storylines are that economic growth is the highest in SSP1 and lowest in SSP3. GDP developments are hence opposite to population developments if one moves from SSP1 to SSP3. The implications for food demand are, therefore, uncertain as higher population means more people to feed, whereas lower total GDP means that there are less total resources to spend on food. In addition, assumptions about dietary preferences and waste management vary across the models, which makes it difficult to predict the implications for food demand directly from the population and GDP drivers.

In MAGNET, the RCP6.0 forcing level has a small negative effect on GDP (approximately -0.22%) and the impact of mitigation is a bit more negative for the GDP development (approximately -0.32%). The GDP effects are small because agriculture is a small sector compared to the global economy and only the mitigation measures affecting N_2O and CH_4 emissions in the agricultural sector were considered in the mitigation scenario by MAGNET.

(7) MAGNET uses a pre-simulation with exogenous GDP targets to estimate the increased production efficiency until 2050

(8) In CAPRI the central SSP2 scenario has been prepared based on a standard long-run baseline using projections from the Aglink (up to 2025) and GLOBIOM (from 2025 onwards) models. In consequence, for the first projection years the macro developments are incompletely harmonized with a "pure" SSP2 scenario (as adopted in GLOBIOM). However, for the simulation of SSP1 and SSP3, CAPRI used the relative changes on macro variables from GLOBIOM such that the differences between scenarios are fully in line with other models.

Figure 10. Total global agricultural production in 2050



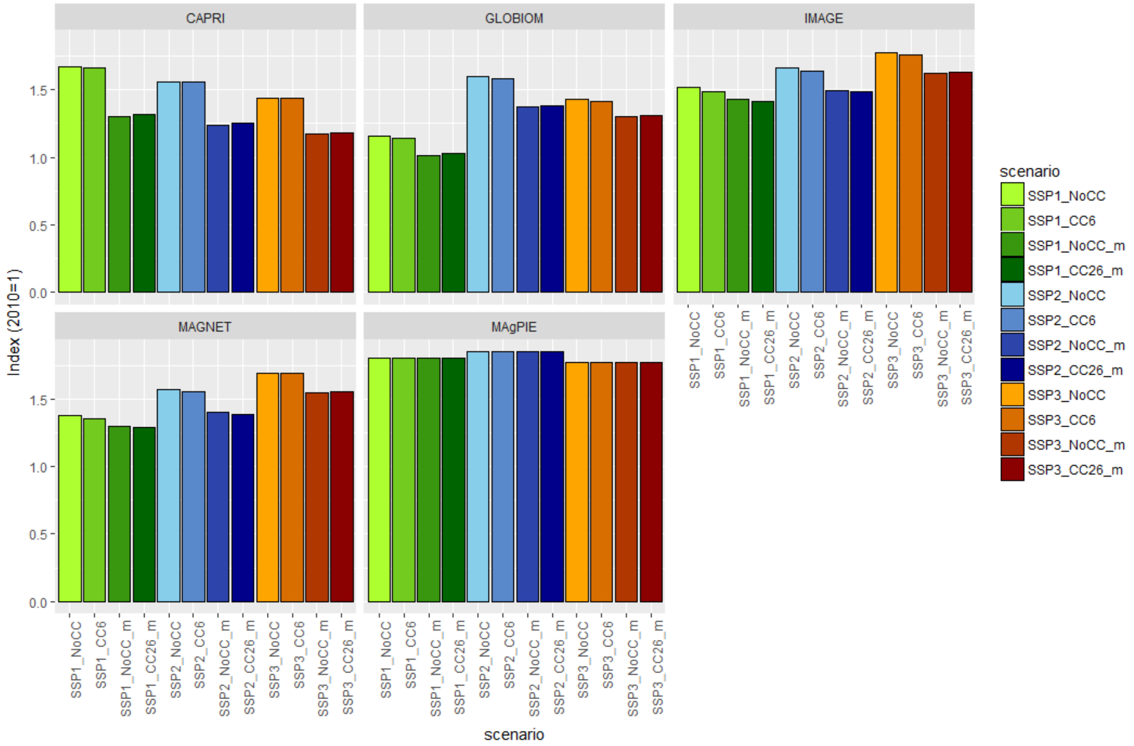
In general, total agricultural production in SSP1 is less than in SSP2 which in turn is less than in SSP3 (Figure 10). This indicates that the demand for agricultural products is more influenced by the population developments and assumptions about waste and dietary preferences than GDP developments. CAPRI exhibits the opposite trend, indicating that GDP developments are a stronger driver than population and that the implementation of dietary changes has been more conservative than in the other models. SSP1 is lower in GLOBIOM as additional preference changes are assumed relative to MAGNET\IMAGE. In SSP3, MAGNET\IMAGE assume additional changes that increase demand and therefore also agricultural production. These additional changes in MAGNET\IMAGE include a 33% waste increase, 25% higher meat consumption and 10% higher import taxes of food. These shifts all induce additional production in MAGNET\IMAGE, but they are not included in GLOBIOM, which only considers a slower reduction in wastes compared to SSP2 and SSP1. In MAgPIE, higher production in SSP3 compared to SSP2 and SSP1 is mainly caused by population growth combined with SSP-specific income-demand responses (e.g., generally healthier diets in SSP1 compared to SSP2 and SSP3).

The impact of RCP6.0 climate forcing on agricultural production can be obtained by comparing the NoCC (first) and the CC6 (second) scenario within an SSP, and the impact of RCP2.6 climate forcing can be seen by comparing the NoCC_m (third) and the No_CC26_m (fourth) scenario. Figure 10 shows that the impact of climate change on agricultural production is negative at the global scale but quite small. It can also be seen that the impact of climate change on total global agricultural production is quite similar between RCP6.0 and RCP2.6, which is due to the selection of median scenarios as they actually imply rather similar yield impacts of the two RCPs in 2050 (see Section 4).

The impact of the mitigation measures compared with taking no mitigation action can be obtained by comparing the CC6 (second) and the CC26_m (fourth) scenario within an SSP. The pure cost of the mitigation measures assuming no climate change can be found by comparing the NoCC (first) and the NoCC_m (third) scenario within an SSP.

Comparing the NoCC and the NoCC_m scenarios it can be seen that the mitigation measures have a negative impact on primary agricultural production for all SSPs in all models. This is unsurprising as the only difference between the two scenarios is the cost of the mitigation measures. Comparing the CC6 and the CC26_m scenarios shows that the mitigation effects are mixed with the differences of RCP2.6 and RCP6.0 on crop yields. While it may be expected that RCP2.6 is more favourable for agricultural production than RCP6.0, this does not hold for all regions, in particular for the 2050 horizon. Furthermore, RCP2.6 and RCP6.0 rely on different pairs of GCMs and crop models in this study. This may have contributed to the finding that the costs of the mitigation measures under CC26_m are dominating over any climate related benefits for agricultural production compared to CC6.

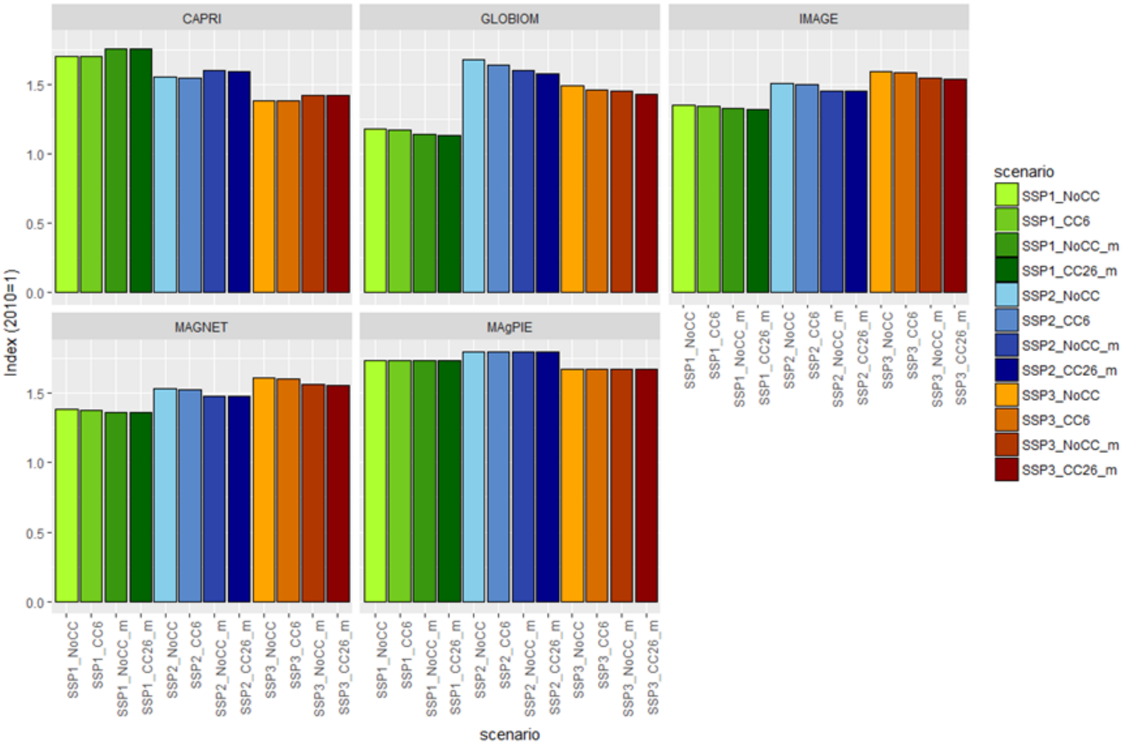
Figure 11. Total production of ruminants in 2050



The additional cost of agricultural mitigation measures reduces production, most notably for rice and especially ruminant meat, in most models (Figure 11). In MAgPIE, final food demand for all products is driven by an exogenous trend at the regional level, and therefore regional demand is not influenced by mitigation policies. With global demand being exogenous, global production of ruminant meat does also not change in the mitigation scenarios. However, in MAgPIE there may be regional changes in production due to shifts in trade across regions. Moreover, production of feed crops changes if regional livestock production is changed due to mitigation policies.

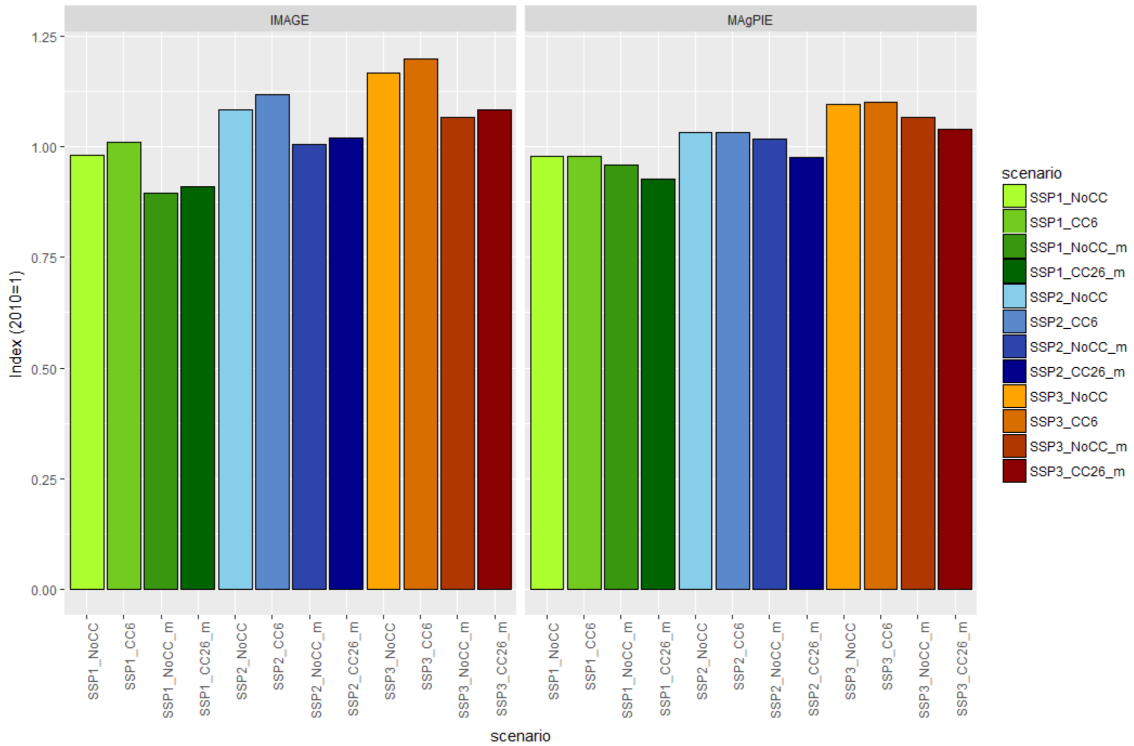
The negative impact of mitigation policies on ruminant meat production is most pronounced in CAPRI. In CAPRI ruminant production in SSP3 is lower than in SSP1 and SSP2, indicating that GDP as a demand driver for meat, reinforced with a dependency of yields on GDP, has a stronger impact than population as demand driver. Moreover, there are no shifts in waste\meat preferences in CAPRI when comparing SSP2 and SSP3, which partially lead to an increase in ruminant production in MAGNET/IMAGE under SSP3.

Figure 12. Total production of non-ruminants in 2050



For most models the production of non-ruminants also decreases due to the mitigation measures (Figure 12). For CAPRI, an increase in production of some commodities (dairy and non-ruminants) is observed. This is due to the large decrease in ruminant meat production induced by the mitigation policies (as ruminant meats have the highest emission intensities their production decreases most). The decrease in production leads to a price increase for ruminant meat and therefore consumers reduce total consumption but also shift to cheaper non-ruminant meat (poultry and pork meat), which has lower emission intensities and therefore is less affected than the ruminant meats. From a technical perspective this is driven by higher cross price elasticities for CAPRI than for MAGNET and the other models do not include cross price elasticities.

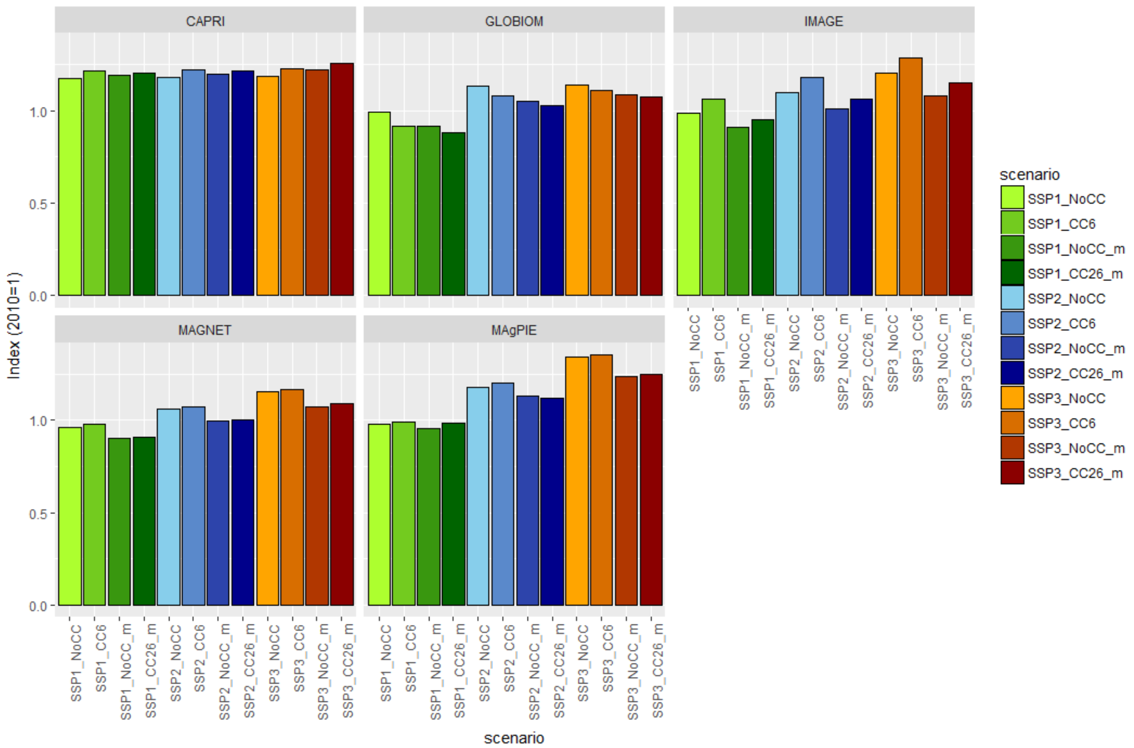
Figure 13. Total land used by agriculture in 2050



Agricultural land cover is lower in the mitigation scenarios (IMAGE, MAgPIE) due to increased use of land for afforestation and bio-energy production (Figure 13). This impact is more pronounced in IMAGE than in MAgPIE or GLOBIOM (not shown). In CAPRI the scenario implementation did not include incentives for mitigation via carbon sequestration and therefore the agricultural area did not decline (in favour of forestry or other land) as in IMAGE or MAgPIE. Regarding the SSP dimension with respect to agricultural land use, the pattern SSP1<SSP2<SSP3 can be observed (also for CAPRI and GLOBIOM, not shown). This is driven by the tighter land use regulation for biodiversity and nature preservation in SSP1 and conversely the relaxing of current regulations in SSP3 (see discussion of SSPs in Section 3), and also by increasingly higher yields and lower meat consumption from SSP3 to SSP2 to SSP1.

The impact of climate change increases land use in IMAGE as lower yields per unit of land induce agricultural producers to seek out additional land for production to meet the demand for food. For MAgPIE the impact of climate change is very small for RCP6.0 and slightly positive for RCP2.6. Under CC26_m agricultural land use is slightly lower compared to NoCC_m, because the exogenous reduction of crop yields due to climate change in combination with land-based mitigation triggers additional investments in agricultural research and development that lead to yield increases (i.e., land expansion becomes less attractive under climate change compared to other options for increasing production).

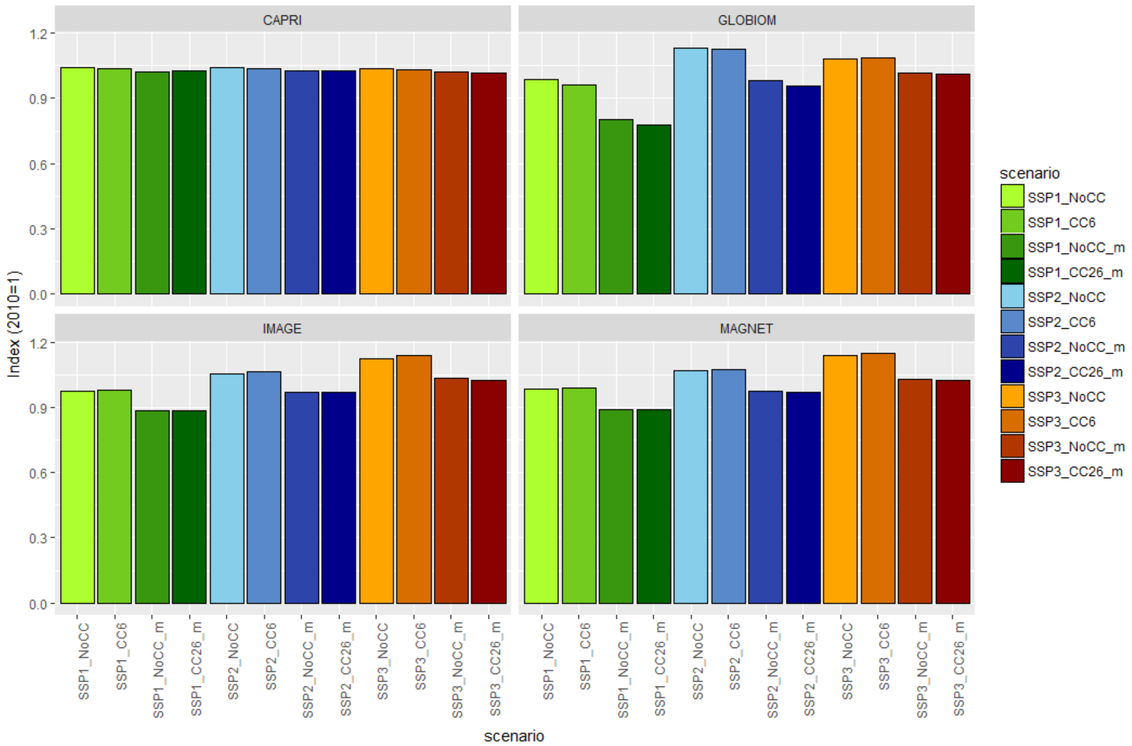
Figure 14. Total land used by crops in 2050



Cropland area generally increases when moving from SSP1 over SSP2 to SSP3 (Figure 14). Climate change increases cropland area in IMAGE\MAGNET, MAgPIE and CAPRI, whereas cropland area decreases in GLOBIOM. For the former four models the lower yield and an inelastic food demand induce the higher land use. For GLOBIOM the mechanism causing the negative impact on cropland is that grasslands are relatively favoured by climate change compared to crops, which leads in some regions to a small shift in the livestock production systems towards more grazing and less reliance on feed crops (Havlik et al. 2015).

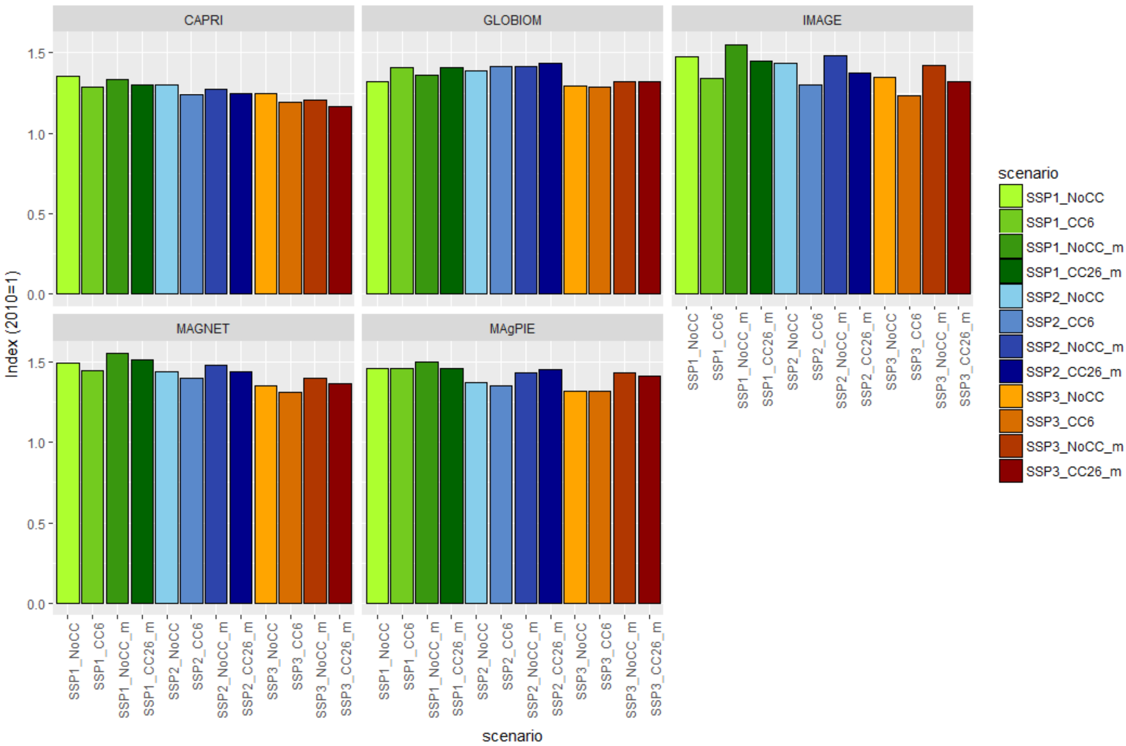
In all models except CAPRI, cropland area decreases due to mitigation measures. The decrease is caused by less available land due to afforestation and demand for bioenergy. In MAgPIE, reduced demand for livestock feed also contributes to this result. However, this does not hold for CAPRI, where mitigation was exclusively incentivised on non-CO_2 emissions. Hence, production shifts within agriculture, more specifically grassland being released from the decreasing ruminant production, explain why cropland expands in CAPRI in contrast to the other models.

Figure 15. Total land used by livestock in 2050



Mitigation measures, in particular afforestation, result in an even larger decrease in area used by livestock in the GLOBIOM, IMAGE and MAGNET models as compared to crops (Figure 15). This is because land is allocated (with imperfect substitution) according to its rental price and cultivating crops gives higher returns to land than livestock. Therefore the decrease in available land due to afforestation impacts more on the livestock sector. In CAPRI this effect is not reflected as afforestation is not specifically considered. The decrease in SSP1 is higher in GLOBIOM due to the strong preference shifts away from ruminant meat in SSP1.

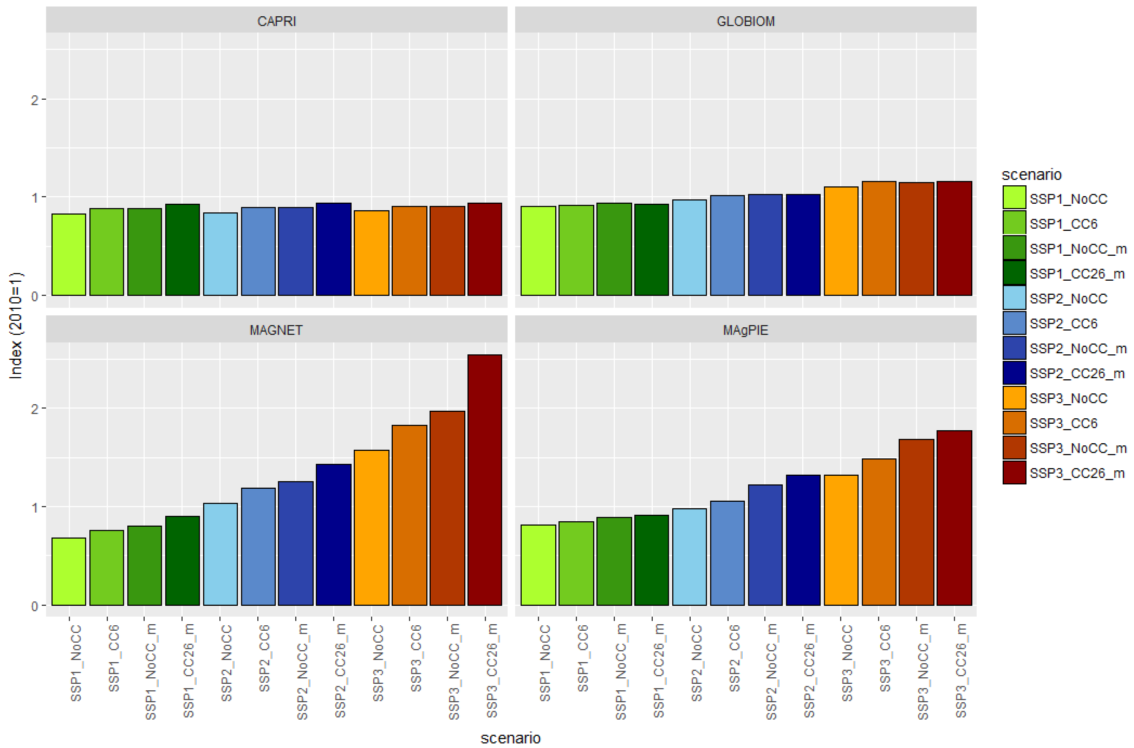
Figure 16. Total crop yield in 2050



Total crop yields (i.e. exogenous biophysical yield shocks + endogenous yield adjustments following commodity market adjustments) are generally higher in SSP1 than in SSP2 and even more compared to SSP3 (Figure 16), as in most models GDP is the key driver for yield differences between SSPs (and GDP decreases from SSP1 to SSP3, see Figure 9). Climate change has in general a negative impact on crop yields at the global level, which is due to the introduced exogenous climate change shocks (see Section 4). In GLOBIOM, global crop yields increase due to climate change because the regions with currently lower yields are more negatively affected by climate change than the temperate regions with usually higher yields. Therefore the low yield regions further loose competitiveness, and even a larger share of the crop production is supplied by developed regions with already relatively high yields. Thus, the increase in total crop yields is the result of a composition effect when aggregating to global scale.

The mitigation policies lead to an increase in crop yields because mitigation measures reduce the amount of available land, which gives an incentive to agricultural producers to use the remaining available land more intensively, hence increasing the use of other inputs per unit of land. As explained above, in CAPRI cropland increases due to the lack of specific policy incentives to increase carbon sequestration, and due to this cropland increase average global crop yields do not increase with mitigation. Moreover, the tax on nitrous oxide emissions penalizes the use of nitrogen fertilizer which rather discourages yield growth in CAPRI (at least globally). In MAgPIE, small climate-induced yield impacts are partly compensated for by endogenous technology adjustments.

Figure 17. Real producer price of crops in 2050



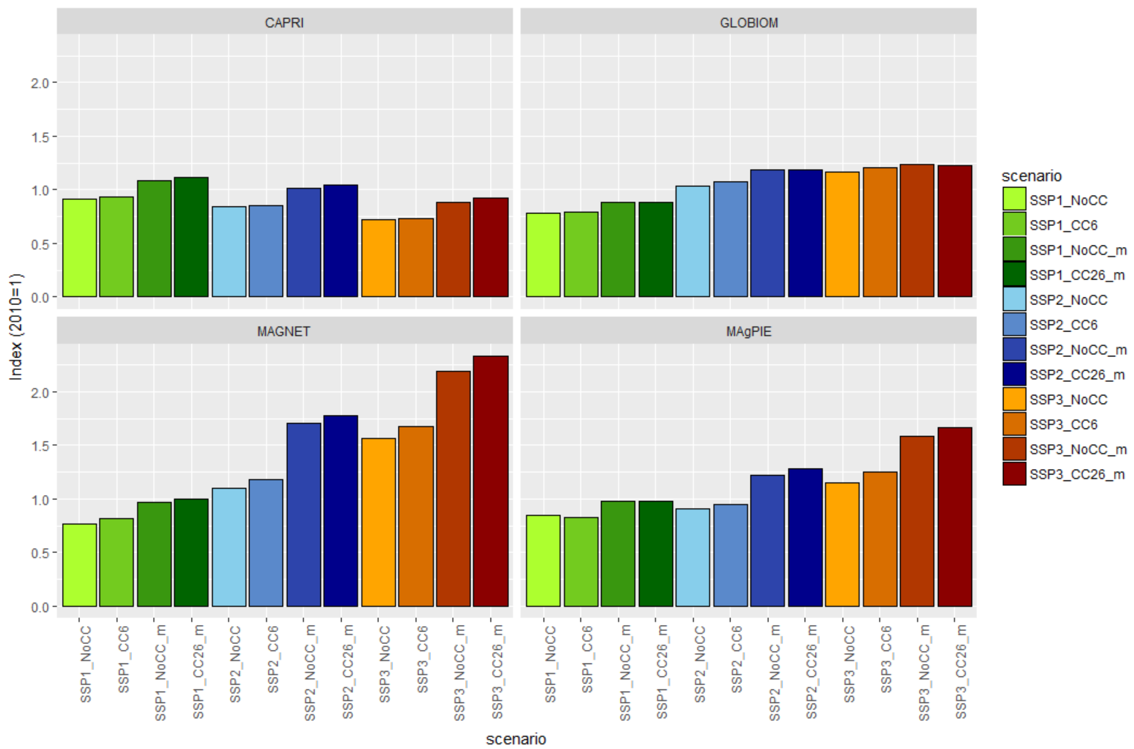
Crop producer prices increase from SSP1 to SSP2 to SSP3 in all models (Figure 17). Compared to 2010, producer prices decrease in SSP1 in all scenarios, whereas they are stable or increase slightly in SSP2 and increase in SSP3. Important drivers on the production side are lower yields in SSP3 than in SSP2 and SSP1. The main demand drivers, population and income, and the interplay between demand and supply determine the prices, which are clearly different in the various models. As shown in Figure 17, price changes are small in GLOBIOM and CAPRI, intermediate in MAgPIE and rather big in MAGNET. The endogenous calibration of technical change in MAGNET contributes to these bigger price effects (see below). In MAgPIE, producer prices are higher in SSP3 due to increased production costs as a result of more restricted trade and augmented costs for additional technological change. Mitigation measures as well as climate impacts induce additional pressures, leading to even higher producer prices. As demand is exogenous in MAgPIE, all the adjustments to climate impacts and mitigation measures have to come from the production side, including reallocation of production through international trade. As agricultural land expansion is limited, especially with strong mitigation policies and restricted trade in SSP3, endogenous yield increase is the main mechanism to compensate.

The bigger price effects in MAGNET can mainly be explained by the calibration of technical change and related labour productivity. In MAGNET, labour productivity is calibrated in a pre-simulation given the development in factor endowments and the GDP targets. MAGNET assumes that agricultural labour productivity is higher than in other sectors based on empirical evidence of the Netherlands Bureau for Economic Policy Analysis (CPB 2003). Given the GDP developments, this implies that agricultural labour productivity in MAGNET is much higher in SSP1 than in SSP2 and especially SSP3. As labour costs have a substantial share in total agricultural production costs, the labour productivity effect together with the yield effect implies that production costs are much lower in SSP1 than in SSP2 than in SSP3. The labour productivity effect is an important determinant of the bigger cost differences between the three SSP scenarios in MAGNET compared to the other models. In addition to the labour productivity effect also land prices are an important driver of producer prices in MAGNET. Furthermore, as shown before in Figure 10, agricultural production increases as we move from SSP1 to SSP2 to SSP3. This implies that higher demand drives increased production despite higher per unit costs due to lower productivity, which then results in higher crop prices. Climate change and mitigation policies further increase the cost of production but the relatively inelastic demand for food keeps demand steady and drives prices even further.

Figure 17 also shows that climate change increases producer prices in almost all cases due to lower yields that restrict supply. The climate change impacts are more pronounced in MAgPIE and MAGNET. As mentioned above, in MAGNET the land prices play a major role in determining producer prices, and as by 2050 land is scarce, especially in the SSP3 scenario, climate change induced lower yields imply then a rapid increase in land prices in this tight market. In MAgPIE, the strongest price effects emerge from the combination of restricted trade and strong mitigation in SSP3.

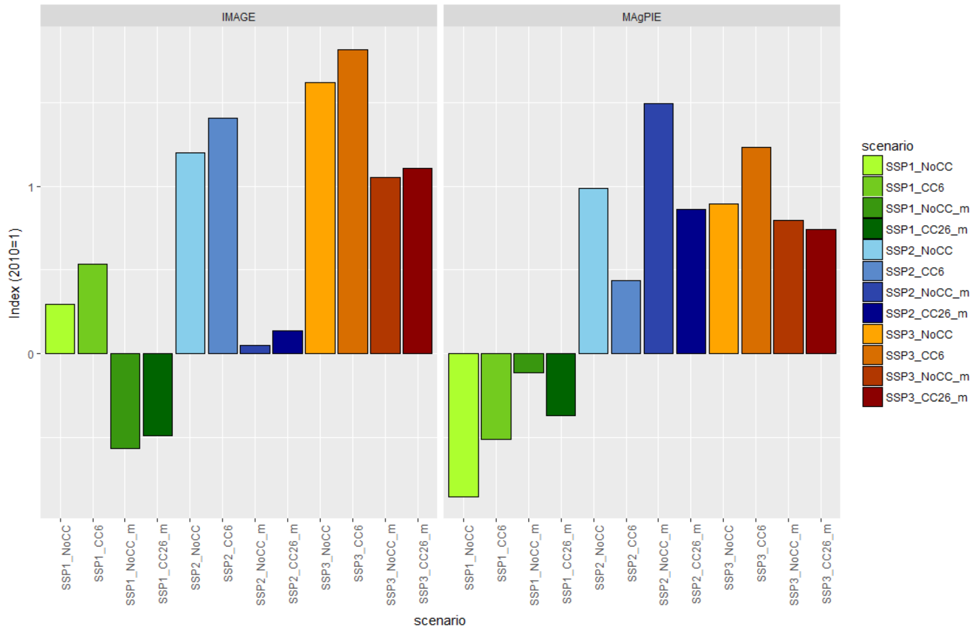
Mitigation efforts also lead to an increase in crop prices. The impact is again more pronounced in MAGNET and MAgPIE than in CAPRI and GLOBIOM. In CAPRI and GLOBIOM, mitigation has almost no impact on crop prices, because the demand for feed crops decreases as a result of reduced livestock production due to the tax on livestock emissions. In MAGNET, the higher impact of mitigation is caused by the lower land availability for agriculture due to afforestation and demand for energy crops. Lower land availability for agriculture puts more pressure on the already tight land markets and leads to an increase in land prices and therefore also food prices. The land pressure is highest in SSP3 and therefore also the impact of mitigation efforts on producer prices is highest in SSP3. For MAgPIE the combination of additional demand for bioenergy crops, non-CO_2 emission taxes and completely inelastic food demand leads to increasing crop prices in the mitigation scenarios.

Figure 18. Real producer price of livestock products in 2050



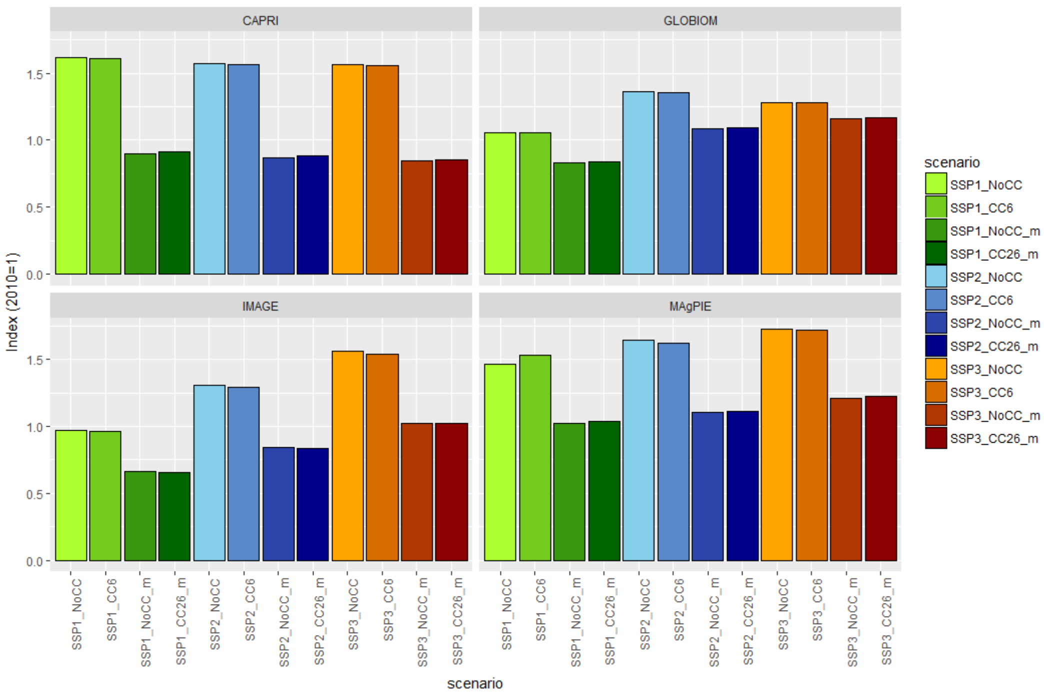
Developments in producer prices for livestock products are similar to those for crops in the models. However, mitigation measures lead to an even higher increase in producer prices for livestock products than for crops (Figure 18). The impact is higher in the livestock sectors, because livestock is more emission intensive and emission taxes directly increase livestock production costs.

Figure 19. Total emissions of CO_2 from land-use change in 2050



CO_2 emissions from land-use change (LUC) are strongly deceasing in most mitigation scenarios due to avoided deforestation (REDD), and afforestation (IMAGE and MAgPIE) (Figure 19). Higher bioenergy production, in contrast, is leading to a slight increase in land-related CO_2 emissions, but reduces CO_2 emissions from the energy system, and may even create a CO_2 sink if used together with carbon capture and storage technology. However, this distinction between afforestation/REDD and bioenergy cannot be derived from this figure and the data reported. In MAgPIE in SSP3, RCP6.0 climate forcing leads to cropland expansion into unprotected tropical forests, which increases CO_2 emissions from land-use change.

Figure 20. Total emissions of CH_4 and N_2O from agriculture in 2050



Mitigation measures strongly reduce agricultural non-CO_2 (i.e. methane and nitrous oxide) emissions in CAPRI, IMAGE and MAgPIE (Figure 20). As the latter two models handle the same marginal abatement cost curves (see Annex 2), the relative reduction in IMAGE and MAgPIE is comparable, though slightly higher in IMAGE. In both models, the relative reduction is comparable across the different SSPs, as in all SSPs much of the mitigation potential is already applied early due to fast increasing carbon taxes. The mitigation effort in CAPRI is similar across the SSPs as the same emission taxes and the same assumptions regarding mitigation technologies are applied across SSPs. Emission reduction is much smaller in GLOBIOM than in the other three models, and differs across SSPs, with SSP3 showing the lowest reduction. This is related to the fact that mitigation in GLOBIOM is mostly based on GHG efficiency improvements through production system composition changes and production relocation across regions, both mediated through prices, not via technical, "add-on", mitigation measures. As discussed above, MAgPIE ignores price-mediated consumption shifts, and therefore, for example, also the pricing of methane emissions does not lead to consumption changes for livestock products, which dampens production decreases and hence limits related emission mitigation in the mitigation scenarios. In IMAGE, technical mitigation measures are combined with system-wide effects due to GHG pricing (calculated via MAGNET). In CAPRI, the decline in agricultural non-CO_2 emissions is similar to the decline in IMAGE and MAgPIE as the same reference (Taylor et al. 2012) has been used for mitigation effects in non-European regions. CAPRI has a quite detailed non-CO_2 mitigation modelling for Europe, but the global results are dominated by other regions.

7 Conclusions and further research

The work presented in this report is a step forward in exploring the scenario space of the impact of future climate change scenarios on agriculture. By trying to harmonize model assumptions (input side) rather than calibrating the models to produce similar results (output side), we are able to produce a wide spectrum of possible future scenarios that can be used for comparison with other research initiatives in this area.

Main scenario results show that across models, global agricultural production is generally lowest in SSP1 and highest in SSP3. This indicates that the demand for agricultural products is more influenced by the population developments and the assumptions about dietary preferences than by the GDP developments. The impact of climate change on agricultural production in 2050 is negative but relatively small at the aggregated global level. A surprising finding might be that the impact of climate change on crop yields is quite similar between RCP6.0 and RCP2.6. However, this is because climate forcing does actually not differ too much in the two RCPs in 2050 and due to the selection of representative median scenarios, the exogenous yield effects are rather similar in RCP6.0 and RCP2.6. In this context it has to be emphasized that, as crop model results have shown, climate impacts will increasingly differ between RCP2.6 and RCP6.0 after 2050. In general, total global crop yields (i.e. exogenous yield shocks + endogenous adjustments following commodity market developments) are higher in SSP1 than in SSP2 and even more compared to SSP3, which is related to the decreasing GDP from SSP1 to SSP3. The mitigation policies lead in most models to an increase in total crop yields because the mitigation measures reduce land availability, which gives agricultural producers an incentive to use the remaining available land more intensively. Nonetheless, the net effect of the climate change mitigation measures on primary agricultural production is negative for all SSPs across all models. Moreover, results indicate that impacts of mitigation policies in terms of reduced agricultural production are larger than the negative impacts due to climate change effects in 2050. This is partially debited to the aforementioned limited impact of the climate change scenarios by 2050 and could change in a longer time horizon. Related to the production effects, climate impacts seem to affect global agricultural prices less strongly than ambitious mitigation policies across the models in this study. The price impact is higher in the livestock sectors than in the crop sectors, because livestock is generally more emission intensive and higher emission taxes directly increase livestock production costs. However, the magnitude of the producer price changes is very different between the models, which requires a deeper analysis, but seems to be mainly due to differences in the general model set-up (especially assumptions on technological change) and assumptions on mitigation measures (e.g. non-CO_2 taxes). With respect to GHG emissions, CO_2 emissions from land-use change are decreasing in most mitigation scenarios due to afforestation and avoided deforestation. The mitigation measures also lead to considerable decreases in agricultural non-CO_2 (methane and nitrous oxide) emissions in most models across all SSPs.

The spectrum of results presented here should be seen as a first step and more work needs to be done to clarify what causes different results across the models as well as to further harmonize the input storylines, specifically with respect to mitigation policies. For example, incentives for energy crop cultivation and credits for LULUCF gains have been different across models, and also the demand side changes that crucially shape the picture under the different SSPs have not been strongly harmonised. Future work in this area could focus on more detailed analysis of the spectrum of results produced in this project, including a closer look at regional results. Drivers of the results which differ across models could be identified. Moreover, robust results across models despite very different implementation or policy mechanisms chosen could be pointed out at more detail. Further harmonization across modelling teams would be necessary to achieve this level of detailed analysis.

As noted above, full harmonization on inputs across models with different structures built for different purposes is not a simple task and one that requires several iterations. The narrative nature of the SSP storylines makes this particularly difficult. Even when the implementation of the SSPs is generally agreed upon, the specific mechanisms to achieve that implementation can vary significantly. The different mechanisms for implementing the SSP storylines across the models and the impact of these decisions on the SSP baseline results should be systematically compared in future work. Similarly, while the targets of the mitigation scenarios were agreed upon across models, i.e., achieving RCP2.6, the operational interpretation of the targets (lacking a closed loop interaction with GCMs that could confirm that targets are met), the policies to achieve RCP2.6, as well as the model mechanisms to implement these policies were left up to the individual modelling teams to decide. Future work in this area could focus on exploring the various policies and model implementation mechanisms in a more systematic way.

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List of abbreviations and definitions

AgMIP	Agricultural Model Intercomparison and Improvement Project
CAPRI	Common Agricultural Policy Regionalised Impact Modelling System
CMIP5	Coupled Model Inter-comparison Project Phase 5
COP21	21st Conference of the Parties to the United Nations Framework Convention on Climate Change
EPIC	Environmental Policy Integrated Climate Model
FAO	Food and Agriculture Organization of the United Nations
FPU	Food Production Unit of the IMPACT model
fullCO2	Scenario setting: crop model simulations assuming full effects from CO2 fertilization by driving models with increasing CO2 concentrations
GCM	General Circulation Model
GDP	Gross Domestic Product
GFDL	Geophysical Fluid Dynamics Laboratory
GFDL-ESM2M	Earth System Model incorporating a GFDL's Modular Ocean Model
GGCM	Global Gridded Crop Growth Model
GHG	Greenhouse Gas
GLOBIOM	Global Biosphere Management Model
HadGEM2-ES	Hadley Global Environment Model 2 - Earth System
IAM	Integrated Assessment Model
IAMC	Integrated Assessment Modelling Consortium
IMAGE	Integrated Model to Assess the Global Environment
IPCC	Intergovernmental Panel on Climate Change
IPSL	Institut Pierre Simon Laplace
IPSL-CM5A-LR	IPSL's Global General Circulation Model developed to study the long-term response of the climate system to natural and anthropogenic forcing as part of CMIP5
ISI-MIP	Inter-Sectoral Impact Model Intercomparison Project
IUCN	International Union for Conservation of Nature
LPJmL	Lund-Potsdam-Jena managed Land model
MAgPIE	Model of Agricultural Production and its Impact on the Environment
MIROC-ESM-CHEM	Atmospheric Chemistry coupled version of the Model for Interdisciplinary Research on Climate – Earth System Model
NoCC	Scenario setting: No climate change
noCO2	Scenario setting: crop model simulations assuming no effects from CO2 fertilization by driving models with static CO2 concentrations.
NorESM1-M	Core version of the Norwegian Climate Center's Earth System Model
pDSSAT	Parallel Decision Support System for Agro-technology Transfer model
RCP	Representative Concentration Pathway

REDD	Reducing Emissions from Deforestation and Forest Degradation
SPAM	Spatial Production Allocation Model
SSP	Shared Socioeconomic Pathway
UNFCCC	United Nations Framework Convention on Climate Change

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Annexes

Annex 1. Model descriptions

In this annex we give a brief description of the five models applied within this study. Further information can be found in the indicated literature.

CAPRI

The Common Agricultural Policy Regionalised Impact (CAPRI)[9] modelling system is an economic large-scale comparative-static agricultural sector model with a focus on the EU (at NUTS 2, Member State and aggregated EU-28 level), but covering global trade with agricultural products as well (Britz and Witzke 2014). CAPRI consists of two interacting modules: the supply module and the market module. The supply module consists of about 280 independent aggregate optimisation models, representing regional agricultural activities (28 crop and 13 animal activities) at Nuts 2 level within the EU-28. These supply models combine a Leontief technology for intermediate inputs covering a low and high yield variant for the different production activities with a non-linear cost function which captures the effects of labour and capital on farmers' decisions. This is combined with constraints relating to land availability, animal requirements, crop nutrient needs and policy restrictions (e.g. production quotas). The non-linear cost function allows for perfect calibration of the models and a smooth simulation response rooted in observed behaviour (cf. Pérez Dominguez et al. 2009; Britz and Witzke 2014). The market module consists of a spatial, non-stochastic global multi-commodity model for 47 primary and processed agricultural products, covering 77 countries in 40 trading blocks. Bi-lateral trade flows and attached prices are modelled based on the Armington assumption of quality differentiation (Armington 1969). The behavioural functions for supply, feed, processing and human consumption in the market module apply flexible functional forms, so that calibration algorithms ensure full compliance with micro-economic theory. The link between the supply and market modules is based on an iterative procedure (cf. Pérez Dominguez et al. 2009; Britz and Witzke 2014).

The CAPRI modelling system is adapted to calculate activity based agricultural emission inventories. CAPRI is designed to capture the links between agricultural production activities in detail (e.g. food and feed supply and demand interactions or animal life cycle), and based on the production activities, inputs and outputs define agricultural GHG emission effects. The CAPRI model incorporates a detailed nutrient flow model per activity and region (which includes explicit feeding and fertilising activities, i.e. the balancing of nutrient needs and availability) and calculates yields per agricultural activity endogenously. With this information, CAPRI is able to calculate endogenously GHG emission coefficients following the IPCC guidelines (IPCC 2006). The IPCC guidelines provide various methods for calculating a given emission. These methods all use the same general structure, but the level of detail at which the calculations are carried out can vary. The IPCC methods for estimating emissions are divided into 'Tiers', encompassing different levels of activity, technology and regional detail. Tier 1 methods are generally straightforward (activity multiplied by default emissions factor) and require less data and expertise than the more advanced Tier 2 and Tier 3 methods. Tier 2 and Tier 3 methods have higher levels of complexity and require more detailed country-specific information on, for example, technology type or livestock characteristics. In CAPRI a Tier 2 approach is generally used for the calculations, however, for activities where the respective information is missing a Tier 1 approach is applied to calculate the GHG emissions (e.g. rice cultivation). A more detailed description of the general calculation of agricultural emission inventories on activity level in CAPRI is given in Pérez Domínguez (2006), Leip et al. (2010) and Pérez Domínguez et al. (2012). Moreover, a detailed description of the modelling approach related to the specifically considered

(9) For more information see: http://www.capri-model.org/

technological GHG mitigation options is presented in Van Doorslaer et al. (2015), Pérez Domínguez et al. (2016) and Fellmann et al. (2017). The technological mitigation options taken into consideration for the mitigation scenarios within the AgCLIM50 project are indicated in Annex 2; for a detailed description of each technology see Pérez Domínguez et al. (2016).

GLOBIOM

The Global Biosphere Management Model (GLOBIOM)[10] (Havlík et al. 2014) is a global recursive dynamic partial equilibrium model of the forest and agricultural sectors, where economic optimization is based on the spatial equilibrium modelling approach (Takayama and Judge 1971). The supply side of the model is based on a bottom-up approach (from land cover, land use, and management systems to production and markets). The agricultural and forest productivity is modeled at the level of grid cells of 5x5 to 30x30 arc-minutes, using biophysical models, such as EPIC (Williams 1995), while the demand and international trade occur at the regional level (from 30 to 53 regions covering the world, depending on the model version and research question). Besides primary products, the model has several final and by-products, for which the processing activities are defined.

The model computes market equilibrium for agricultural and forest products by allocating land use among production activities to maximize the sum of producer and consumer surplus, subject to resource, technological and policy constraints. The level of production in a given area is determined by the agricultural or forestry productivity in that area (dependent on suitability and management), by market prices (reflecting the level of demand), and by the conditions and cost associated to conversion of the land, to expansion of the production and, when relevant, to international market access. Trade flows are balanced out between different specific geographical regions. Trade is furthermore based purely on cost competitiveness as goods are assumed to be homogenous. This allows tracing of bilateral trade flows between individual regions.

By including not only the bioenergy sector but also forestry, cropland and grassland management, and livestock management, the model allows for a full account of all agriculture and forestry GHG sources. GLOBIOM accounts for ten sources of GHG emissions, including crop cultivation N_2O emissions from fertilizer use, CH_4 from rice cultivation, livestock CH_4 emissions, CH_4 and N_2O emissions from manure management, N2O from manure applied on pasture, and above and below ground biomass CO_2 emissions from biomass removal after converting forest and natural land to cropland.

IMAGE

The Integrated Model to Assess the Global Environment (IMAGE)[11] framework (Stehfest et al. 2014) describes various global environmental change issues using a set of linked submodels describing the energy system, the agricultural economy and land use, natural vegetation and the climate system. The socioeconomic models distinguish 26 world regions, while the natural ecosystems mostly work at a 5x5 minutes and 30x30 minutes grids. Agricultural demand, production and trade are modelled via the MAGNET model (Woltjer et al. 2014), which is integral part of the IMAGE framework in most scenario studies. The use of bio-energy plays a role at several components of the IMAGE system. First of all, the potential for bio-energy is determined using the land use model, taking into account several sustainability criteria, i.e. the exclusion of forests areas, agricultural areas and nature reserves (see van Vuuren et al. 2009). In the energy submodel, the demand for bio-energy is assessed by describing the cost-based competition of bio-energy versus other energy carriers (mostly in the transport, electricity production,

([10]) For more information see: www.iiasa.ac.at./GLOBIOM
([11]) For more information see: IMAGE 3.0 Documentation

industry and the residential sectors). The resulting demand for bio-energy crops is combined with the demand for other agricultural products within a region to determine future land use. For this purpose, the LPJml model is used, determining yields as a function of land and climate conditions and assumed changes in technology. Based on these spatially explicit attainable yields, and other suitability considerations, land use is allocated on the grid level. Finally, the emissions associated with land use and land-use change and the energy system are used in the climate model (MAGICC-6) to determine climate change, which then affects all biophysical submodels.

MAGNET

The Modular Applied GeNeral Equilibrium Tool (MAGNET)[12] model is a multi-regional, multi-sectoral, applied general equilibrium model based on neo-classical microeconomic theory (Nowicki at al. 2007; Nowicki at al. 2009; van Meijl et al. 2006; Woltjer et al. 2014). It is an extended version of the standard GTAP model (Hertel 1997). The core of MAGNET is an input–output model, which links industries in value added chains from primary goods, over continuously higher stages of intermediate processing, to the final assembly of goods and services for consumption. Primary production factors are employed within each economic region, and hence returns to land and capital are endogenously determined at equilibrium, i.e., the aggregate supply of each factor equals its demand. On the consumption side, the regional household is assumed to distribute income across savings and (government and private) consumption expenditures according to fixed budget shares. Private consumption expenditures are allocated across commodities according to a non-homothetic CDE expenditure function and the government consumption according to Cobb-Douglas expenditure function.

The MAGNET model, in comparison to GTAP, uses a more general multilevel sector specific nested CES (constant elasticity of substitution) production function, allowing for substitution between primary production factors and (land, labor, capital and natural resources) and intermediate production factors and for substitution between different intermediate input components (e.g. energy sources, and animal feed components). MAGNET includes an improved treatment of agricultural sectors (like various imperfectly substitutable types of land, the land use allocation structure, a land supply function, substitution between various animal feed components, Meijl et al. 2006; Eickhout et al. 2009), agricultural policy (like production quotas and different land related payments, Nowicki et al. 2009) and biofuel policy (capital-energy substitution, fossil fuels-biofuels substitution, Banse et al. 2008). On the consumption side, a dynamic CDE expenditure function is implemented which allows for changes in income elasticities when purchasing power parity (PPP)-corrected real GDP per capita changes. Segmentation and imperfect mobility between agriculture and non-agriculture labor and capital are introduced in the modelling of factors markets,

MAGNET is linked to IMAGE (Stehfest at al. 2014) to account for biophysical constraints and feedbacks. MAGNET uses information from IMAGE on agricultural land availability, crop yield changes, pasture use intensification and changes in livestock production systems. In this way, also environmental feedbacks such as depletion of high-yield land and climate impact on yields are implemented in MAGNET.

MAgPIE

The Model of Agricultural Production and its Impacts on the Environment (MAgPIE)[13] is a partial-equilibrium agriculture and land use model (Lotze-Campen et al. 2008; Schmitz et al. 2012; Popp et al. 2014; Bodirsky et al. 2015). Based on a regional demand for agricultural products and biophysical endowments on a regular geographic 0.5°×0.5°

([12]) For more information see: http://www.magnet-model.org/
([13]) For more information see: https://www.pik-potsdam.de/research/projects/activities/land-use-modelling/magpie

grid resolution, the model generates optimal land use patterns by minimizing global production costs. The recursive dynamic nature of the model is reflected in a 10-year time-step optimization, where optimal land use patterns from the previous period are taken as a starting point for the current period. The initial period is calibrated to the arable area reported by the FAO. At the top level, MAgPIE operates on ten socioeconomic regions. The demand for food is regionally defined and given as an exogenous trend to the model, encompassing 16 crop and 5 livestock types. The estimates for calorie intake for each region are obtained from a country cross-section regression analysis on population and GDP (Bodirsky et al. 2015). In addition to food, the agricultural demand consists also of feed, material and bioenergy demand. Feed demand is based on feed baskets defined for each livestock production activity and depends on regional efficiencies, while material demand is implemented in proportion with food demand. The supply side in MAgPIE is determined by different production costs, biophysical crop yields and availability of water. The information on rain-fed and irrigated crop yields, water availability and water requirements for every grid-cell are by default provided by the LPJmL (Lund-Potsdam-Jena with managed Land) model (Müller and Robertson 2014). The objective function of the optimization process is to minimize global agricultural production costs. The main decision on how to allocate land for cropping activities is based on four types of production costs and interregional restrictions on trade. In the MAgPIE model four different types of costs are defined: factor requirements, technological change, land conversion and transport costs. Factor requirements costs are defined per ton of produced crop type and differentiated between rainfed and irrigated production systems. They represent costs of capital, labour and intermediate inputs (such as fertilizers and other chemicals) and are implemented at the regional scale using the cost-of-firm GTAP data. Crop production can be increased in a region by investing in yield increasing technological change (Dietrich et al. 2014), or by expansion of agricultural production into other non-agricultural areas suitable for plant cultivation. Land conversion from forest and natural vegetation into arable land comes at region-specific costs. Transport costs are calculated from the GTAP database and assure paying for a quantity of goods transported to the market in a unit of time needed for covering the distance. All MAgPIE regions fulfil part of their demand by domestic production, which is founded on regional self-sufficiency ratios. If domestic production does not cover regional demand, goods are imported from regions with excess production. Export shares and self-sufficiency ratios are calculated from the FAOSTAT database for the initial year (1995). Trade between regions can be liberalized in future time periods by relaxing the trade barrier, and thus allowing for a certain share of goods freely traded, based on regional comparative advantage. In every time step, trade is balanced at the global level (Schmitz et al. 2012).

Annex 2. Emission sources and mitigation measures included in the models

CH_4 emission sources and mitigation measures	Remind-MAgPIE			Message-GLOBIOM			IMAGE		
	Sources	Mitigation measures included?	Feedbacks in AgSystem?	Sources	Mitigation measures included?	Feedbacks in AgSystem?	Sources	Mitigation measures included?	Feedbacks in AgSystem?
CH4 emissions from on-field burning of agricultural waste	CH4 emissions from on-field burning of agricultural waste including stubble, straw, etc. (IPCC category 4F)	no	no	From FAOSTAT, kept contastant	no	no	regionally specified fraction of agricultural residues burnt. Emission factor per gC	yes, MAC curve EPA and Lucas et al. 2007	no, only via MAGNET
CH4 emissions from Animal waste management (AWM)	methane emissions from animal waste management (AWM)	yes, MAC curve Lucas et al. 2007	yes, emission pricing can alter trade patterns and investments in TC	Emission factor per animal/production system	yes/no	yes	emission from animal waste, emission factor per animal head	yes, MAC curve EPA and Lucas et al. 2007	no, only via MAGNET
CH4 emissions from enteric fermentation	methane emissions from enteric fermentation	yes, MAC curve Lucas et al. 2007	yes, emission pricing can alter trade patterns and investments in TC	Emission factor per animal/production system	yes/no	yes	emissions from enteric fermentation, as a function of animal type and feed composition	yes, MAC curve EPA and Lucas et al. 2007	no, only via MAGNET
CH4 emissions from rice production	methane emissions from rice production	yes, MAC curve Lucas et al. 2007	yes, emission pricing can alter trade patterns and investments in TC	emission from irrigated rice, emission factor per ha	yes/no	yes	emission from irrigated rice, emission factor per ha	yes, MAC curve EPA and Lucas et al. 2007	no, only via MAGNET

CH_4 emission sources and mitigation measures	MAGNET			CAPRI-EU			CAPRI-nonEU		
	Sources	Mitigation measures included?	Feedbacks in AgSystem?	Sources	Mitigation measures included?	Feedbacks in AgSystem?	Sources	Mitigation measures included?	Feedbacks in AgSystem?
CH4 emissions from on-field burning of agricultural waste	no	no	no	no	no	no	no	no	no
CH4 emissions from Animal waste management (AWM)	IMAGE model	yes, 1. MAC curve EPA and Lucas et al. 2007; 2. Emmision price; Both are implemented as a tax on production	Economic feedbacks via price changes; substitution between products as agricultrual products become more expensive depending on intensity of emmisions and cost of abatement	CH4MAN, Efs per activity	AD	yes	CH4MAN, Efs per ton of product	via exogenous change in Efs	via exogneous cost per ton
CH4 emissions from enteric fermentation	IMAGE model	yes, 1. MAC curve EPA and Lucas et al. 2007; 2. Emmision price; Both are implemented as a tax on production	Economic feedbacks via price changes; substitution between products as agricultrual products become more expensive depending on intensity of emmisions and cost of abatement	CH4ENT, Efs per activity	Breeding, vaccination, feed additives	yes	CH4ENT, Efs per ton of product	via exogenous change in Efs	via exogneous cost per ton
CH4 emissions from rice production	IMAGE model	yes, 1. MAC curve EPA and Lucas et al. 2007; 2. Emmision price; Both are implemented as a tax on production	Economic feedbacks via price changes; substitution between products as agricultrual products become more expensive depending on intensity of emmisions and cost of abatement	CH4RIC, Efs per activity	Rice measures	yes	CH4RIC, Efs per ton of product	via exogenous change in Efs	via exogneous cost per ton

N_2O emission sources and mitigation measures	Remind-MAgPIE			Message-GLOBIOM			IMAGE		
	Sources	Mitigation measures included?	Feedbacks in AgSystem?	Sources	Mitigation measures included?	Feedbacks in AgSystem?	Sources	Mitigation measures included?	Feedbacks in AgSystem?
N2O emissions from agricultural waste burning	Anthropogenic N2O emissions from ag waste burning	no	no	From FAOSTAT, kept contastant	no	no	regionally specified fraction of argicultural residues burnt. Emission factor per gC	yes, MAC curve EPA and Lucas et al. 2007	no, only via MAGNET
Direct and indirect N2O emissions from animal waste management (AWM)	Direct and indirect (leaching&volatilisation) nitrous oxide emissions from animal waste management (AWM)	yes, MAC curve Lucas et al. 2007	yes, emission pricing can alter trade patterns and investments in TC	Emission factor per animal/production system	yes/no	yes	emission from animal waste, emission factor per animal head	yes, MAC curve EPA and Lucas et al. 2007	no, only via MAGNET
Direct and indirect N2O emissions from cropland soil fertilization (mineral fertilizer and manure application)	Direct and indirect (leaching&volatilisation) nitrous oxide emissions from cropland soil fertilization, including most importantly inorganic fertilizers and manure application on croplands	yes, MAC curve Lucas et al. 2007	yes, emission pricing can alter trade patterns and investments in TC	Direct and indirect (leaching&volatilisation) nitrous oxide emissions from cropland soil fertilization, including most importantly inorganic fertilizers and manure application on croplands	yes/no	yes	direct and indirect N2O emissions from fertilizer and manure spreading	yes, MAC curve EPA and Lucas et al. 2007	no, only via MAGNET
Direct and indirect N2O emissions from manure excreted on pasture range and paddock	Direct and indirect (leaching&volatilisation) nitrous oxide emissions from manure excreted on pasture range and paddock	no	no	Direct and indirect (leaching&volatilisation) nitrous oxide emissions from cropland soil fertilization, including most importantly inorganic fertilizers and manure application on croplands	yes/no	yes	direct and indirect N2O emissions from manure spreading and manure left during grazing		no, only via MAGNET

N_2O emission sources and mitigation measures	MAGNET			CAPRI-EU			CAPRI-nonEU		
	Sources	Mitigation measures included?	Feedbacks in AgSystem?	Sources	Mitigation measures included?	Feedbacks in AgSystem?	Sources	Mitigation measures included?	Feedbacks in AgSystem?
N2O emissions from agricultural waste burning	no	no	no	no	no	no	no	no	no
Direct and indirect N2O emissions from animal waste management (AWM)	IMAGE model	yes, 1. MAC curve EPA and Lucas et al. 2007; 2. Emmision price; Both are implemented as a tax on production	Economic feedbacks via price changes; substitution between products as agricultrual products become more expensive depending on intensity of emmisions and cost of abatement	N2OMAN, Efs per activity	Breeding, low N feeding	yes	N2OMAN, Efs per ton of product	via exogenous change in Efs	via exogneous cost per ton
Direct and indirect N2O emissions from cropland soil fertilization (mineral fertilizer and manure application)	IMAGE model	yes, 1. MAC curve EPA and Lucas et al. 2007; 2. Emmision price; Both are implemented as a tax on production	Economic feedbacks via price changes; substitution between products as agricultrual products become more expensive depending on intensity of emmisions and cost of abatement	N2OAPP, N2OSYN, N2OAMM, N2OLEA, N2OHIS, N2OCRO Efs per activity	Breeding, low N feeding, fertilisation measures, histosol protection	yes	N2OAPP, N2OSYN, N2OAMM, N2OLEA, N2OHIS, N2OCRO Efs per ton of product	via exogenous change in Efs	via exogneous cost per ton
Direct and indirect N2O emissions from manure excreted on pasture range and paddock	IMAGE model	yes, 1. MAC curve EPA and Lucas et al. 2007; 2. Emmision price; Both are implemented as a tax on production	Economic feedbacks via price changes; substitution between products as agricultrual products become more expensive depending on intensity of emmisions and cost of abatement	N2OGRA, Efs per activity	Breeding, low N feeding, fertilisation measures	yes	N2OGRA, Efs per ton of product	via exogenous change in Efs	via exogneous cost per ton

Annex 3. SSP implementation across models

		SSP1			SSP2			SSP3			Comments
	Income grouping	*low*	*medium*	*high*	*low*	*medium*	*high*	*low*	*medium*	*high*	
	Land-use change regulation	*strong*			*medium*			*weak*			*This describes the level and quality of governance regarding land use. Strong = strong forest protection, low availability of non-agricultural land for conversion; weak = weak forest protection, high availability of non-agricultural land for conversion*
GLOBIOM	**Land use policies**	Protected areas in cat I and II IUCN tripled in forest and other natural vegetation as from 2020			Protected areas in cat I and II IUCN increased by 50% in forest and other natural vegetation as from 2020 (Aichi target)			Current protected areas			Here we implement explicitly or implicitly the current land use policies such as protected areas or land use related measures in the European Common Agricultural Policy (CAP)
IMAGE-MAGNET	**Forest protection**	current protected areas extended to 2x Aichi target (34%), gradually introduced from 2010-2050			current protected areas extended to Aichi target (17%), gradually introduced from 2010-2050			current protected areas			
IMAGE-MAGNET	**Deforestation**	Deforestation due to sources other than agricultural expansion decreasing to zero in 2020			Deforestation due to sources other than agricultural expansion decreasing to zero in 2040			Deforestation due to sources other than agricultural expansion decreasing to zero in 2060			
IMAGE-MAGNET	**Urban area**	Expansion of built-up area a function of population and urbanization (Klein Goldewijk in prep)			Expansion of built-up area a function of population and urbanization (Klein Goldewijk in prep)			Expansion of built-up area a function of population and urbanization (Klein Goldewijk in prep)			
MAGPIE	**Forest protection**	Linear increase of protected forest areas by factor 4 between 2010 and 2100			Linear increase of protected forest areas by factor 1.5 between 2010 and 2100			Constant protected forest areas at 2010 levels after 2010			Protect forest areas in 2010 amount to 12.5% of total global forest area (FAO 2010; Popp et al. 2014)
CAPRI	**Forest protection**	Model endogenous adjustments emulated through a 5 EUR/t carbon price			Model endogenous adjustments emulated through a 2.5 EUR/t carbon price			Model endogenous adjustments emulated through a 0 EUR/t carbon price			

		SSP1			SSP2			SSP3			Comments
	Income grouping	*low*	*medium*	*high*	*low*	*medium*	*high*	*low*	*medium*	*high*	
	Land productivity growth	*rapid*	*rapid*	*medium*	*medium*			*slow*			SSP2: declining growth rate for high-income countries, converging rates for low-income countries; SSP1: faster catch-up of low-income countries, but also taking into account sustainability issues; SSP3: lower rates everywhere; SSP4: no convergence between low-income and high-income regions. SSP5: high yield growth
GLOBIOM	**Crops: Yields**	Technological change as a function of GDP.			Technological change as a function of GDP.			Technological change as a function of GDP.			Based on historical FAOSTAT data and GDP, relationship between the two has been estimated. SSP GDP projections have then been used to estimate future yield developments (Goetz et al. forthcoming)
GLOBIOM	**Crops: Input intensity**	Elasticity of variable inputs incl. fertilizer use wrt technological change: 0.75			Elasticity of variable inputs incl. fertilizer use wrt technological change: 1.00			Elasticity of variable inputs incl. fertilizer use wrt technological change: 1.25			Depending on the SSP, technological change is more or less input intensive.
GLOBIOM	**Livestock: Feed conversion efficiency**	Relative difference in the speed of technological change in the crop sector implemented on the SSP2 feed conversion efficiency developments.			Future projections have been made globally for SSP2 by extending past trend, but taking into account a biophysical "ceiling"			Relative difference in the speed of technological change in the crop sector implemented on the SSP2 feed conversion efficiency developments.			Past growth in efficiencies for dairy, beef, poultry and pigs has been estimated based on FAOSTAT (Soussana et al. 2012). Future projections have been made globally for SSP2 by extending this trend, but taking into account a biophysical "ceiling". The regional projections and projectsions for other SSPs are based on the differentials in average crop yield growth.
GLOBIOM	**Livestock: Endogenous productivity growth**	Faster adoption of more efficient livestock production systems.			GLOBIOM default assumption			Slower adoption of more efficient livestock production systems.			The model is allowed to transition faster from one livestock production system to another and hence increase the production efficiency (Havlík et al. 2014)
IMAGE-MAGNET	**Yield increase**	Yield increase as a function of GDP increase as e.g. suggested by Powell et al. 2013, and see IMAGE paper			Yield increase as a function of GDP increase as e.g. suggested by Powell et al. 2013, and see IMAGE paper			Yield increase as a function of GDP increase as e.g. suggested by Powell et al. 2013, and see IMAGE paper			
IMAGE-MAGNET	**Nitrogen fertilzer use**	20% increase in nitrogen use efficiency relative to FAO projection			Nitrogen use based on FAO projection			20% reduction in nitrogen use efficiency relative to FAO projection			
IMAGE-MAGNET	**Irrigation**	Smaller increase in irrigated area than in SSP2 due to increased sustainability concerns; large increase in irrigation efficiency			FAO projection on irrigated area expansion (Alexandratos & Bruinsma 2012); medium increase in irrigation efficiency			More expansion of irrigated areas than in SSP2 due to higher food demand and less constraints; small increase in irrigation efficiency			
IMAGE-MAGNET	**Livestock intensification**	Higher efficiency increase than in SSP2, approaching SSP2 intensitiy levels earlier, e.g. in 2030 instead of in 2050, and in 2050 instead of in 2100.			FAO projection as far as available, and own expert estimation			Lower efficiency increase than in SSP2, approaching SSP2 intensitiy levels later e.g. only in 2050 instead of in 2100.			

	Income grouping	SSP1 low	SSP1 medium	SSP1 high	SSP2 low	SSP2 medium	SSP2 high	SSP3 low	SSP3 medium	SSP3 high	Comments
	Land productivity growth	*rapid*	*rapid*	*medium*		*medium*			*slow*		SSP2: declining growth rate for high-income countries, converging rates for low-income countries; SSP1: faster catch-up of low-income countries, but also taking into account sustainability issues; SSP3: lower rates everywhere; SSP4: no convergence between low-income and high-income regions. SSP5: high yield growth
MAgPIE	**Yield increase**	Endogenous yield increase			Endogenous yield increase			Endogenous yield increase			Investments in yield-increasing technological change are based on cost-effectivness compared to land expansion (Dietrich et al 2013)
MAgPIE	**Discount rates / Governance**	4%/yr globally representing strong governance -> low costs for land expansion and intensification			7%/yr globally representing medium governance -> medium costs for land expansion and intensification			10%/yr globally representing weak governance -> high costs for land expansion and intensification			All scenarios start at 7%/yr globally in 2005 and converge towards the scenario specific discount rate by 2030. Based on Wang et al. (2016).
MAgPIE	**Nitrogen fertilzer use**	Soil nitrogen uptake efficiency converges to 65% globally by 2050, and rises to 70% by 2100			Soil nitrogen uptake efficiency converges to 60% globally by 2050; constant thereafter.			Soil nitrogen uptake efficiency converges to 55% globally by 2050, and rises to 60% by 2100			Soil nitrogen uptake efficiency scenarios are based on Bodirsky et al (2014). The global average soil nitrogen uptake efficiency in 2010 is 53%.
MAgPIE	**Livestock intensification**	Strong intensification. Slow down of intensification in developed regions.			Medium intensification			Low intensification			Future scenarios of livestock productivity are derived based on informed guesses, taking into account past productivity improvements, GDP projections, cultural particularities, and the general scenario story-line.
CAPRI	**Crops: Yields**	75% of the exogenous yield growth from GLOBIOM implementation is applied for each scenario, 25% CAPRI endogenous			75% of the exogenous yield growth from GLOBIOM implementation is applied for each scenario, 25% CAPRI endogenous			75% of the exogenous yield growth from GLOBIOM implementation is applied for each scenario, 25% CAPRI endogenous			
CAPRI	**Crops: Input intensity**	Model endogenous adjustments emulated through a 5 EUR/t carbon price			Model endogenous adjustments emulated through a 2.5 EUR/t carbon price			Model endogenous adjustments emulated through a 0 EUR/t carbon price			So far variable inputs other than land and feed are only represented as a general non-agricultural price index, without quantity information.
CAPRI	**Livestock: Feed conversion efficiency**	Model endogenous adjustments emulated through a 5 EUR/t carbon price			Model endogenous adjustments emulated through a 2.5 EUR/t carbon price			Model endogenous adjustments emulated through a 0 EUR/t carbon price			Feed energy and protein prices ensure that nutrient intake and animal production relate to each other as in the reference run during scenarios. But changes in these requirements are possible ot reflect feed efficiency gains.

	Income grouping	SSP1 (low / medium / high)	SSP2 (low / medium / high)	SSP3 (low / medium / high)	Comments
	Environmental Impact of food consumption	*low*	*medium*	*high*	*This describes preferences and consumer behaviour, and is on top of endogenous effects resulting from GDP development. Low = realtively low caloric intake, relatively low animal calorie share, low waste; high = realtively high caloric intake, relatively high animal calorie share, high waste*
GLOBIOM	**Food demand**	Income elasticities recalibrated to reflact to reflect the better management of domestic waste in developed countries, consumption per capita is in the regions assumed almost constant animal protein demand is reduced in regions where more than 75 g prot/cap/day are consumed for animal and vegetal products. A minimum consumption of 25 g prot/cap/day of animal calories is ensured but red meat consumption is reduced to 5 g prot/cap/day (target remains possible through non ruminant meat, eggs and milk). For developing regions, an increase in animal protein intake at 75 g prot/cap/day and a reduction of root consumption at a level of 100 kcal/cap/day	Default setup	SSP2 elasticities used, difference in demand is due to the difference in GDP	Developments in future consumption preferences are captured in the income elasticity values. (Valin et al. 2014)
GLOBIOM	**Losses & Wastes**	Losses & Wastes reduction as function of GDP	Losses & Wastes reduction as function of GDP	Losses & Wastes reduction as function of GDP	Based on FAO (2011), the relationship between GDP and development of losses and wastes arising during "Postharvest handling and storage, Processing, Distribution/Retail" were considered. For two groups of products, a strong relationship to GDP was identified: Oilseeds&Pulses and Milk

		SSP1			SSP2			SSP3			Comments
	Income grouping	*low*	*medium*	*high*	*low*	*medium*	*high*	*low*	*medium*	*high*	
	Environmental Impact of food consumption	*low*			*medium*			*high*			*This describes preferences and consumer behaviour, and is on top of endogenous effects resulting from GDP development. Low = realtively low caloric intake, relatively low animal calorie share, low waste; high = realtively high caloric intake, relatively high animal calorie share, high waste*
IMAGE-MAGNET	**Food demand**	Less meat and dairy: meat&dairy consumption 5%, 10%, 20% and 30% lower than endogenous outcome, in 2020, 2030, 2050, and 2100 respectively, for high and medium income regions; implemented via a "taste factor"			Default setup			More meat and dairy: meat&dairy consumption 5%, 10%, 20% and 30% higher than endogenous outcome, in 2020, 2030, 2050, and 2100 respectively; implemented via a "taste factor"			
IMAGE-MAGNET	**Waste**	Reduction of waste by 1/3 (current waste is about 33%): Implemented as a 11% total efficiency increase in producing and using of agri-food products. This 11% will be divided between agriculture, intermediate use of agri food in processin and final consumption						Incease of waste by 1/3 (current waste is about 33%): Implemented as a 11% total efficiency decrease in producing and using of agri-food products. This 11% will be divided between agriculture, intermediate use of agri food in processin and final consumption			
MAgPIE	**Food demand**	Food demand sytem leading to medium food demand and low demand for livestock products. Additionally, food waste is strongly reduced, leading to a maximum demand of 3000kcal/capita/day.			Food demand sytem leading to medium food demand and low demand for livestock products. Additionally, livestock share in rich countries are not falling below 15%.			Food demand sytem leading to high food demand and high demand for livestock products. Additionally, livestock share in rich countries are not falling below 15%.			The share of per-capita demand and animal-based calories is income and time dependent (Bodirsky et al 2015). The functional forms in the food demand models is chosen accoding to the storyline.
CAPRI	**Food demand**	Any excess of protein consumption from animal origin beyond 40 g/d/head is reduced by 50% up to 2050 and by 25% by 2030			Model default setup			Model default setup			

	Income grouping	SSP1 low medium high	SSP2 low medium high	SSP3 low medium high	Comments
	International trade	*globalized*	*regionalized*	*regionalized*	*This not only covers abolishing or maintaining of current agricultural trade regulations, but also in general more or less integrated and globalized world markets. SSP4 = in principle globalized trade, but limited food access and high vulnerability in poor countries*
GLOBIOM	**Agricultural trade barriers**	Trade costs are reduced to between countries but intercontinental trade costs are increased to capture regional preference	GLOBIOM default assumption	Trade costs are increased for all international commodity flows	
IMAGE-MAGNET	**Agricultural trade barriers**	Export subsidies and import tariffs reduction for all sectors, in 2020 50% reduction compared with 2010, 2030 abolished.	Default setup	Default setup	
IMAGE-MAGNET	**Regional preference**	Preference for products from own region: Implemented by the introduction of an import taxes for all agri products. 2030: 5%, 2050: 10%, 2100 10%.	Default setup	Food security concerns: Implemented by the introduction of an import taxes for all agri products. 2030: 5%, 2050: 10%, 2100 10%.	
MAgPIE	**Agricultural trade barriers**	Agricultural trade barriers decline by 1% per year	Agricultural trade barriers decline by 0.5% per year	Agricultural trade barriers decline by 0% per year	There are two tradepools in the model, one with trade according to historical trade patterns, and another one with free trade according to comparative advantages. Reducing trade barriers increases the free trade pool (Schmitz et al 2012)
CAPRI	**Agricultural trade barriers**	Business as usual for explicit trade policies and standard assumptions on Armington elasticities and transport costs	Business as usual for explicit trade policies and standard assumptions on Armington elasticities and transport costs	Business as usual for explicit trade policies and standard assumptions on Armington elasticities and transport costs	Trade barriers for agriculture are explicit and have been revised (IPTS project). Scenarios on trade liberalization are standard in CAPRI.

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