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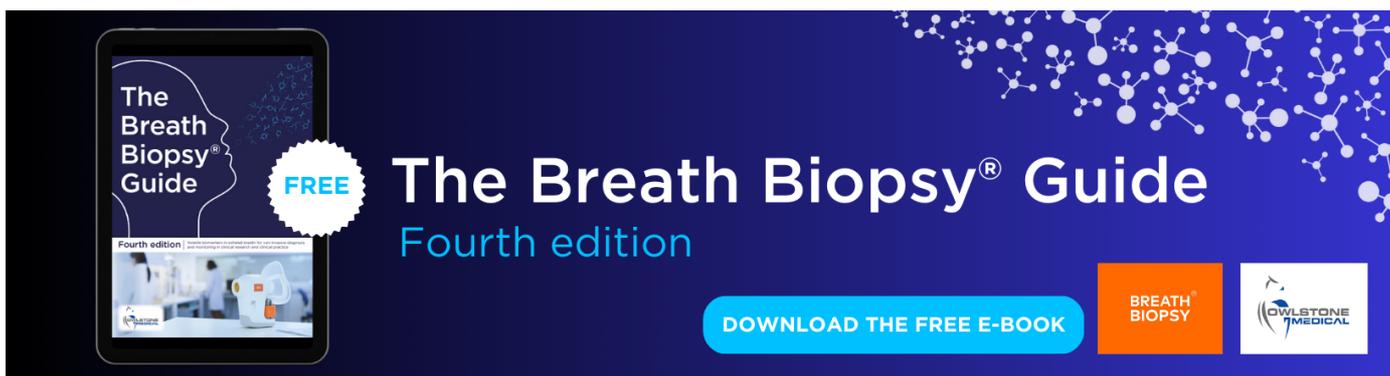
## Comparing impacts of climate change and mitigation on global agriculture by 2050

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## LETTER

# Comparing impacts of climate change and mitigation on global agriculture by 2050

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Supplementary material for this article is available [online](#)

## Abstract

Systematic model inter-comparison helps to narrow discrepancies in the analysis of the future impact of climate change on agricultural production. This paper presents a set of alternative scenarios by five global climate and agro-economic models. Covering integrated assessment (IMAGE), partial equilibrium (CAPRI, GLOBIOM, MAGPIE) and computable general equilibrium (MAGNET) models ensures a good coverage of biophysical and economic agricultural features. These models are harmonized with respect to basic model drivers, to assess the range of potential impacts of climate change on the agricultural sector by 2050. Moreover, they quantify the economic consequences of stringent global emission mitigation efforts, such as non-CO<sub>2</sub> emission taxes and land-based mitigation options, to stabilize global warming at 2 °C by the end of the century under different Shared Socioeconomic Pathways. A key contribution of the paper is a vis-à-vis comparison of climate change impacts relative to the impact of mitigation measures. In addition, our scenario design allows assessing the impact of the residual climate change on the mitigation challenge. From a global perspective, the impact of climate change on agricultural production by mid-century is negative but small. A larger negative effect on agricultural production, most pronounced for ruminant meat production, is observed when emission mitigation measures compliant with a 2 °C target are put in place. Our results indicate that a mitigation strategy that embeds residual climate change effects (RCP2.6) has a negative impact on global agricultural production relative to a no-mitigation strategy with stronger climate impacts (RCP6.0). However, this is partially due to the limited impact of the climate change scenarios by 2050. The magnitude of price changes is different amongst models due to methodological differences. Further research to achieve a better harmonization is needed, especially regarding endogenous food and feed demand, including substitution across individual commodities, and endogenous technological change.

## 1. Introduction

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 while safeguarding food security and recognizing the particular vulnerabilities of food production systems to the adverse impacts of climate change.

The agricultural sector is, on the one hand, directly affected by climate change due to altered weather conditions and resulting biophysical effects (Challinor *et al* 2014, Rosenzweig *et al* 2014). On the other hand, agriculture, forestry and other land use are responsible for almost a quarter of anthropogenic greenhouse gas (GHG) emissions (Smith *et al* 2014), and reduction of emissions from agriculture is necessary to achieve the global climate change goals (Reisinger *et al* 2013, Gernaat *et al* 2015, Wollenberg *et al* 2016). In order to achieve ambitious climate mitigation targets, both CO<sub>2</sub> and non-CO<sub>2</sub> GHG emissions need to be reduced substantially. Furthermore, achieving the ambitious targets is conditional on the large-scale availability of negative emissions technologies, in particular carbon sequestration through afforestation and bioenergy systems connected to carbon capture and storage (BECCS), in the second half of the century (Clarke *et al* 2014, Anderson and Peters 2016). Without these technologies, even more modest stabilization would require substantially larger GHG emissions reductions in the medium term, further increasing the impacts of mitigation on the food system (Havlik *et al* 2015a). However, both afforestation and BECCS are very land use intense negative emissions technologies (Smith *et al* 2016) and therefore affect agriculture via the land markets. In this context an integrated multi-model assessment taking into account both the range of potential climate change impacts as well as climate change mitigation measures, and their interaction, is required to provide insights for effective and efficient policy decision making.

Until now, the quasi-totality of global agricultural sector assessments considered either climate change impacts or climate change mitigation policies. The assessment of impacts of climate change on agricultural production and food security has a long tradition (Rosenzweig and Parry 1994, Parry *et al* 2004, Nelson *et al* 2010). Recent work as part of the Agricultural Model Inter-comparison and Improvement Project (AgMIP) (Rosenzweig *et al* 2013) has examined (and narrowed) the differences between models in estimated impacts on agriculture of a certain level of climate change through systematic model inter-comparison (Nelson *et al* 2013, 2014, von Lampe *et al* 2014, Lotze-Campen *et al* 2014). This work focused on a single ‘middle-of-the-road’ Shared Socioeconomic Pathway (SSP 2, O’Neill *et al* 2014) and climate impacts for a single high-emission Representative Concentration Pathway (RCP 8.5, Vuuren *et al* 2011). Wiebe *et al* (2015) extended these analyses to three SSPs and three RCPs. The land use and agricultural sector implications of ambitious climate change stabilization policies, without taking into account the climate change impacts, were recently analysed in a multi-model setup within the SSP-RCP framework by Popp *et al* (2017).

Havlik *et al* (2015a) analyzed in a single model consistent scenario setup both unmitigated climate change impacts on the agricultural sector and the

effects of ambitious mitigation scenarios, however they ignored the interactions between these two dimensions. Finally, also in a single model study, Hasegawa *et al* (2015) represented the scenarios in an integrated way, where the mitigation scenario took systematically into account the residual climate change impacts. Their results show, similarly to the results from Havlik *et al* (2015a) that at least in the medium term, till 2050, the climate stabilization scenarios would have a more severe impact on food security than unmitigated climate change.

In this paper, we present a set of alternative scenarios by different models, harmonized with respect to basic model assumptions, to assess the range of potential economic impacts of climate change on the agricultural sector by 2050, as well as the economic consequences of stringent global emission mitigation efforts (e.g. bioenergy use, afforestation, reduction of methane and nitrous oxide emissions in agriculture) aiming to stabilize global warming at 2 °C by the end of the century under different SSPs. For this purpose, the analysis covers selected combinations of SSPs and RCPs. This approach allows us to assess the interplay of socioeconomic developments, climate change impacts and climate mitigation policies on the agricultural sector while taking into account the model related uncertainties. Agro-economic models can present quite different results when analyzing economic and related impacts of climate change on agriculture. As the focus is usually on the model results, it is often not clear if differences are due to the model specification (e.g. partial or general equilibrium models), model parameterization (e.g. supply, demand or trade elasticities), scenario assumptions (e.g. future economic, population and policy developments) or to data sources. Therefore, this paper not only focuses on the scenario results but also on the harmonization of key model inputs and the comparison of what is driving model results.

## 2. Methodology

### 2.1. Model framework

For the analysis, five global economic models were employed (table 1, supplementary material S1 available at [stacks.iop.org/ERL/13/064021/mmedia](https://stacks.iop.org/ERL/13/064021/mmedia)). 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 spatial resolution and the level of disaggregation of the agricultural sector are very different across the models, as both are functions of each model’s history and original purpose. Furthermore, the employed models differ in a number of other characteristics. For

Table 1. Key characteristics of the models used.

Model	Type	Economy coverage <sup>a</sup>	Agricultural policies	Bioenergy	Agricultural supply	Final demand	Trade
MAGNET (Woltjer <i>et al</i> 2014)	CGE	Full economy, agriculture (10), processed food (9)	Price wedges, quota (adjusted from GTAP)	Endogenous 1st generation (incl. biofuel targets)	Nested CES	CDE private demand <sup>b</sup> and Cobb-Douglas utility	Armington spatial equilibrium
GLOBIOM (Havlik <i>et al</i> 2014)	PE	Agriculture (25), forestry, bioenergy	Implicitly assumed unchanged	Exogenous demand from MESSAGE energy system model	Leontief at production system and grid level	Iso-elastic <sup>b</sup>	Enke-Samuelson-Takayama-Judge spatial equilibrium
MAGPIE (Lotze-Campen <i>et al</i> 2008)	PE	Agriculture (21), bioenergy, water	Implicitly assumed unchanged	Exogenous demand from energy system model	Leontief	Scenario-specific exogenous projections	Scenario-specific trends in regional self-sufficiency rates
CAPRI (Britz and Witzke 2014)	PE	Agriculture (42), processed food (28)	Explicitly represented	Endogenous 1st generation calibrated to exogenous baseline	Regional agri. nonlinear mathematical programming	Second order flexible generalized Leontief indirect utility	Armington spatial equilibrium
IMAGE (Stehfest <i>et al</i> 2014)	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: MAGNET = Modular Applied GeNeral Equilibrium Tool; GLOBIOM = Global Biosphere Management Model; MAGPIE = Model of Agricultural Production and its Impact on the Environment; CAPRI = Common Agricultural Policy; Regionalised Impact Modelling System; IMAGE = Integrated Model to Assess the Global Environment; CGE = Computable General Equilibrium; PE = Partial Equilibrium; IAM = Integrated Assessment Model; CES = Constant elasticity of substitution; CDE = Constant difference of elasticities.

<sup>a</sup> Number of primary agricultural and processed food sectors.

<sup>b</sup> Elasticities adjusted over time.

instance, some of the models can be used to depict alternative levels of second-generation bioenergy production, while others have no explicit representation of bioenergy or focus on feedstock use for first-generation biofuels, electricity and/or heating (Wicke *et al* 2015). Three models have spatially explicit representations of bilateral trade flows, even if differing in the specific approach used (Berkum and van Meijl 2000, van Tongeren *et al* 2001). Food 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 systems and gets its agro-economic information by a linkage to MAGNET. Although the five models employed are state of the art and are frequently used for agro-economic analyses, including the assessment of climate change impacts on agriculture, it has to be kept in mind that they are simplifications of reality and designed to illustrate complex processes. The models are theoretical constructs representing economic processes by a set of variables and quantitative relationships between

them, using simplified assumptions and not able to specifically address all factor dynamics. Furthermore, behaviour is represented by structural parameters which are quantified using historical data and are often kept constant over time.

## 2.2. Scenarios–setup and assumptions

The experimental design to analyze the impact of climate change and climate change mitigation under three contrasting socioeconomic developments (SSP1/SSP2/SSP3) is outlined in table 2, indicating also the adaptation challenge for agriculture within the different SSPs. Row A depicts a set of reference scenarios to reflect socioeconomic changes without climate change impacts (NoCC). Scenarios in row B explore climate impacts from RCP6.0 (median impact across different crop model and climate model combinations, without CO<sub>2</sub> fertilization). Comparing scenarios in row A and row B delivers the climate change RCP6.0 impacts on agriculture ('CC RCP6.0' effect). Scenarios in row C depict the effects of ambitious mitigation efforts (e.g. bioenergy use, afforestation, reduction of agricultural non-CO<sub>2</sub> emissions) on agriculture

**Table 2.** Scenario setting, including residual impacts and the adaptation dimension.

Cluster	Climate change impacts	Mitigation	Focus	SSP1 'Sustainability'	SSP2 'Middle of the Road'	SSP3 'Fragmentation'
Challenges for adaptation and mitigation				Low	Medium	High
A	NoCC	NoMitig	No climate change	SSP1_NoCC	SSP2_NoCC	SSP3_NoCC <sup>a</sup>
B	RCP6.0 <sup>a</sup>	NoMitig	A + Climate change impacts	SSP1_CC6 <sup>b</sup>	SSP2_CC6	SSP3_CC6
C	NoCC	2 °C mitigation	A + Mitigation measures for 2 °C stabilization without residual climate change impacts	SSP1_NoCC_m	SSP2_NoCC_m	SSP3_NoCC_m
D	RCP2.6 <sup>a</sup>	2 °C mitigation	C + residual climate change impacts	SSP1_CC26_m	SSP2_CC26_m	SSP3_CC26_m

<sup>a</sup> Based on a scenario with median climate impacts (across different crop model/climate model combinations), without CO<sub>2</sub> fertilization.

<sup>b</sup> The full matrix of selected SSP-RCP combinations has been designed to stretch across very different but consistent futures such as SSP1\_CC26\_m or SSP3\_CC6. At the same time, for analytical purposes we included also less likely combinations of these two dimensions such as SSP3\_NoCC or SSP1\_CC6.

**Table 3.** General and specific SSP elements for the agricultural and land use sector.

SSP elements	SSP1			SSP2			SSP3		
	Country income groupings								
	Low	Med	High	Low	Med	High	Low	Med	High
<b>Economic growth</b>	High			Medium			Low		
<b>Population growth</b>	Low			Medium			High	Medium	Medium
<b>Land use change regulation</b>	High			Medium			Low		
<b>Land productivity growth</b> - Crop yields - Tech. progress in livestock	High	High	Medium	Medium			Low		
<b>Environmental impact of food consumption</b> - Food demand - Losses and waste management	Low			Medium			High		
<b>International trade</b>	Globalized			Regionalized			Regionalized		

Source: adjusted from Popp *et al* (2017).

in order to stabilize global warming at 2 °C above pre-industrial levels (with no residual climate change impact). A comparison of scenario A and C gives the pure impact of mitigation policies on agriculture ('Mitigation' effect). Scenarios in row D add the climate impacts of the RCP2.6 (without CO<sub>2</sub> fertilization) to the scenarios in row C and thus allow to analyze the climate change impact in a 2 °C world ('CC RCP2.6' effect)<sup>9</sup>. Finally, scenarios D compared to scenarios A provide the 2 degree mitigation effect including the residual climate change impacts ('Mitigation + Residual CC'). While the effects 'CC RCP 2.6' and 'Mitigation' are used for diagnostic purposes, comparing the full climate change effects of 'CC RCP 6.0' and the full mitigation effects 'Mitigation + RCP 2.6' allows to directly evaluate the benefits/costs of climate stabilization compared to a world without climate policies.

<sup>9</sup> For MAGNET, we run additional SSP\_CC26 scenarios to identify more precisely the 'CC RCP 2.6' effect in comparison to the NoCC scenario as there are strong interaction effects between the mitigation and climate change effects.

The following sections briefly describe the underlying assumptions for the SSPs, climate change related crop yield impacts, and mitigation measures in the agricultural sector. Model inputs are partly harmonized but the specific implementation can differ between the models.

### 2.1.1. Socioeconomic narratives

The SSPs represent different global futures, with narratives for future demographic and economic developments, lifestyle, policies and institutions, technology, and environmental protection (O'Neill *et al* 2017). In this paper we focus on SSP1, SSP2 and SSP3 (tables 3 and 4). SSP 2 (Middle of the Road) is a pathway with modest overall growth in population and incomes, and a slow pace of overall trade liberalization. SSP 1 (Sustainability) features lower population growth, higher growth in per capita incomes, faster globalization and a higher environmental awareness (less waste, less meat consumption), while SSP 3 (Regional Rivalry) describes a more fragmented world with less international trade, higher population growth, a lower growth in per capita incomes and less environmental

**Table 4.** Shared Socio-economic Pathway (SSP) scenario description.

SSP	SSP name	Description
SSP1	Sustainability	A future pathway with low challenges for adaptation and mitigation. A pathway that makes relatively good progress towards sustainability, with sustained efforts to achieve development goals, while reducing resource intensity and fossil fuel dependency. Elements that contribute to this are an open globalised economy, rapid development of low-income countries, a reduction of inequality (globally and within economies), rapid technology development, low population growth and a high level of awareness regarding environmental degradation. More environmental awareness reduces food waste, the appetite for meat as well as making land use regulation stricter.
SSP2	Middle of the Road	A business as usual scenario. In this world, trends typical of recent decades continue, with some progress towards achieving development goals, reductions in resource and energy intensity at historical rates, and slowly decreasing fossil fuel dependency. A world with only medium challenges for adaptation and mitigation.
SSP3	Regional Rivalry	A world with high challenges for adaptation and mitigation. A world which is separated into regions characterized by extreme poverty, pockets of moderate wealth and a bulk of countries that struggle to maintain living standards for a strongly growing population. Regional blocks of countries have re-emerged with little coordination between them. Countries focus on achieving energy and food security goals within their own region. The world has de-globalized, and international trade, including energy resource and agricultural markets, is severely restricted. Population growth in this scenario is high as a result of limited improvements in education and low economic growth.

Source: based on O'Neill *et al* (2017).

awareness. The models used in this paper are harmonized to the SSP quantitative projections on population (Kc and Lutz 2017) and economic GDP growth (Dellink *et al* 2017), and also assumptions related to agricultural and land use sectors are aligned to the extent possible (van Meijl *et al* 2017, see supplementary material S2 for a description of the harmonised and model specific SSP assumptions). The GLOBIOM implementation builds on Fricko *et al* (2017), IMAGE/MAGNET on van Vuuren *et al* (2017), and MAGPIE on Kriegler *et al* (2017). The level of technological change differs across SSPs and most models focus on yields. In GLOBIOM, IMAGE/MAGNET and CAPRI, SSP-related yields are a function of GDP, whereas in MAGPIE yields are endogenous depending on cost effectiveness compared with land expansion and a SSP-specific discount rate. In MAGNET, labour and capital productivity differs between SSP scenarios as these are calibrated to preserve scenario-specific GDP growth rates (see Robinson *et al* 2014 and supplementary material S1 for information on the general treatment of technological change in the models).

### 2.2.2. Climate change related crop yield impacts

We rely on a representative selection of climate change impact scenarios on crop and grassland yields. The selection is based on data on climate change impacts on crops yields from global gridded crop models (GGCM) for different climate scenarios (Rosenzweig *et al* 2014). The climate scenarios are bias-corrected implementations (Hempel *et al* 2013) of the RCPs as provided by general circulation models (GCM) from the CMIP5 data archive (Taylor *et al* 2012). Three GGCMs have been selected based on data availability: EPIC (Williams 1995), LPJmL (Bondeau *et al* 2007, Müller and Robertson 2014), and pDSSAT

(Jones *et al* 2003, Elliott *et al* 2014). This large set of biophysical yield shock scenarios (up to 15 scenarios, 5 GCMs  $\times$  3 GGCMs per RCP) could not be used to drive all global economic models, so that a subset was selected. For this, yield impacts were computed for the global aggregation for each GCM $\times$ GGCM combination. For the aggregation to global-scale climate change impacts on biophysical crop yields, gridded crop yield projections from the GGCMs were aggregated to changes in global crop and pasture production using 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 grassland areas were extracted from Fader *et al* (2010). For each of the two different emission pathways (RCP6.0 and RCP2.6) studied here, we only consider one biophysical crop yield scenario from the 15 possible GCM $\times$ GGCM combinations by selecting the median case. The median case is defined by the globally aggregated climate change impacts on crop yields. 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), whereas the median scenario for RCP6.0 is represented by the combination of the GCM HadGEM2-ES (Jones *et al* 2003) and the GGCM DSSAT (Elliott *et al* 2014). The crop model simulations cover several crops which differ by GGCM from only four (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 Annex table A.1. The regionally aggregated climate change impacts on yields have been used in the economic models as exogenous shocks on the annual yield growth rates up to 2050 (Annex table A.2).

RCP2.6 and RCP6.0 have been selected for their representativeness of the 2 degree mitigation and the no mitigation policy under SSP2, respectively, at the end of the 21st century (van Vuuren *et al* 2011, Riahi *et al* 2017). However, it has to be noted that they are not distinctively different in 2050 (the time horizon in this paper), as in 2050, GHG concentrations of RCP2.6 are still close to peak concentration levels whereas RCP6.0 has still relatively low GHG concentrations in 2050, so that the radiative forcing of RCP2.6 and RCP6.0 are quite similar in 2050. RCP8.5 was not considered as even without climate change mitigation, none of SSP1–3 is likely to reach a GHG concentration that is high enough to be compatible with RCP8.5 (Riahi *et al* 2017). While GHG concentration levels and climate impacts on crop yields on average will further increase beyond 2050 (Rosenzweig *et al* 2014), several of the economic models are not well prepared to cover scenarios beyond 2050. Hence, this analysis was confined to 2050.

### 2.2.3. Agricultural GHG mitigation

Agriculture is the largest contributor to the global anthropogenic non-CO<sub>2</sub> GHG emissions of methane and nitrous oxide, accounting for about 10%–12% of total global GHG emissions (Smith *et al* 2014). Despite the importance of agricultural non-CO<sub>2</sub> emissions, their mitigation has received somewhat less attention than the land-based mitigation potential of CO<sub>2</sub> (e.g. bioenergy production, afforestation and reduced emissions from deforestation and forest degradation). The non-CO<sub>2</sub> emission sources and mitigation measures covered in the models are CH<sub>4</sub> emissions from (i) enteric fermentation, (ii) rice production, (iii) animal waste management, and (iv) on-field burning, and N<sub>2</sub>O emissions from (i) manure excreted on pasture, range and paddock, (ii) cropland fertilization (mineral fertilizer and manure applications), (iii) animal waste management, and (iv) agricultural waste burning. The model specific implementation of these non-CO<sub>2</sub> emissions and measures are described in table A.2. Next to these non-CO<sub>2</sub> mitigation options we include REDD (reduced emissions from deforestation and forest degradation), afforestation and bioenergy as land-based CO<sub>2</sub> mitigation options that affect agriculture by competing on the land market. The mitigation scenarios are implemented in all scenarios via a carbon price. A carbon price implemented on direct non-CO<sub>2</sub> emissions from the agricultural sector leads to adoption of more GHG efficient production systems and dedicated technologies but also to reduction of agricultural production because it indirectly increases production cost. Carbon price implemented on CO<sub>2</sub> emissions from land use and land use change fosters reduction of deforestation and further afforestation and hence also contributes to higher production cost through increased land rents. The carbon price implemented on fossil fuel related CO<sub>2</sub> emissions leads to increased demand for biomass for

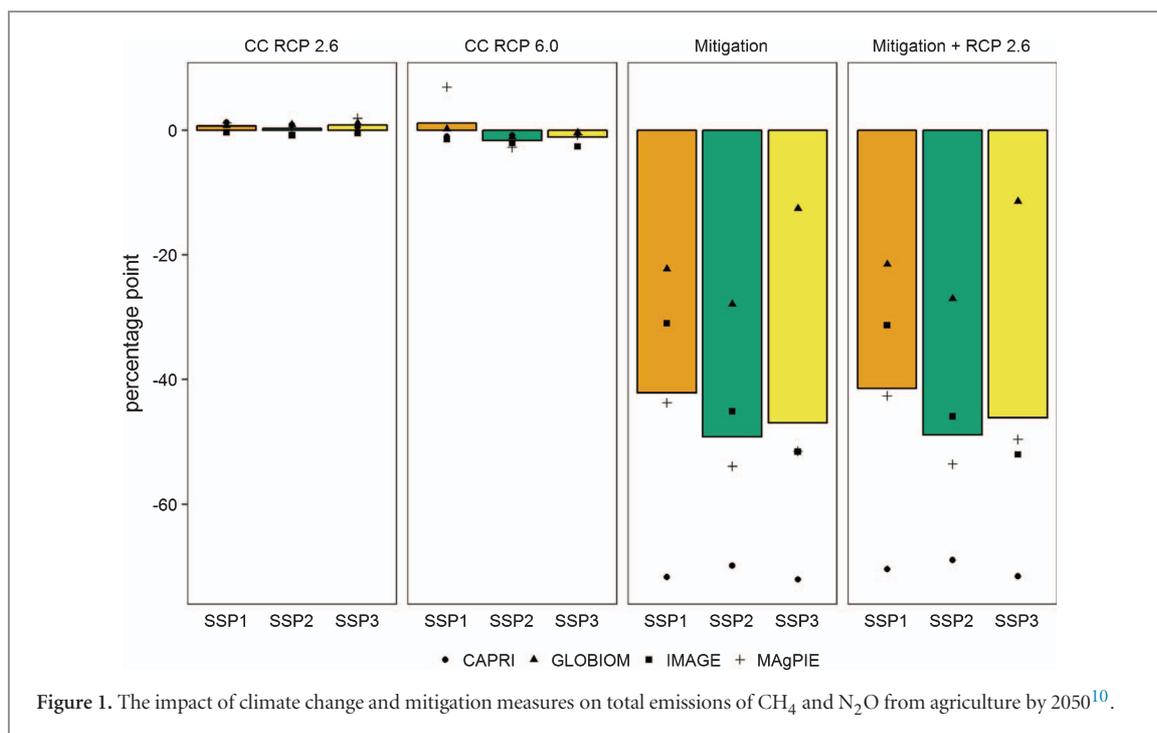
bioenergy production, and also contributes to competition for land. Finally, the tax for residual emissions is paid by producers, which transforms then into higher producer market prices because of the increased cost. The producers can transfer only part of the tax cost to consumers because the price elastic demand. All these dynamics lead to rising food prices which reduce food consumption. All models represent endogenously mitigation of non-CO<sub>2</sub> emissions, however some models do not represent the full land use and hence approximate the impacts of the carbon price on land use by land use projections from other models (MAGNET), and except for MAGNET and IMAGE, the models do not represent directly the energy system, and hence use biomass demand projections from other models to simulate the substitution of fossil fuels by bioenergy. The positive income effect of tax income recycling or increased agricultural income is not considered by most models (only MAGNET takes these effects into account).

## 3. Results

### 3.1. Agricultural non-CO<sub>2</sub> emissions

Mitigation measures strongly reduce agricultural non-CO<sub>2</sub> emissions by about 40%–45% in CAPRI, IMAGE (MAGNET) and MAgPIE (figure 1), with methane and nitrous oxide emissions being reduced by 50% and 30%, respectively. As IMAGE and MAgPIE use the same marginal abatement cost curves (Lucas *et al* 2007), the relative reduction in both models is similar, 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 in all 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 because mitigation in this implementation of GLOBIOM is mostly based on GHG efficiency improvements through changes in production system composition and production relocation across regions, both mediated through prices, but not via technological mitigation measures.

MAgPIE neglects price-mediated food demand 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 reductions in the mitigation scenarios. A reduction of global feed demand is however possible via trade of livestock products from regions with higher feeding efficiencies. In IMAGE, technological mitigation measures are combined with system-wide effects due to GHG pricing (calculated via MAGNET).



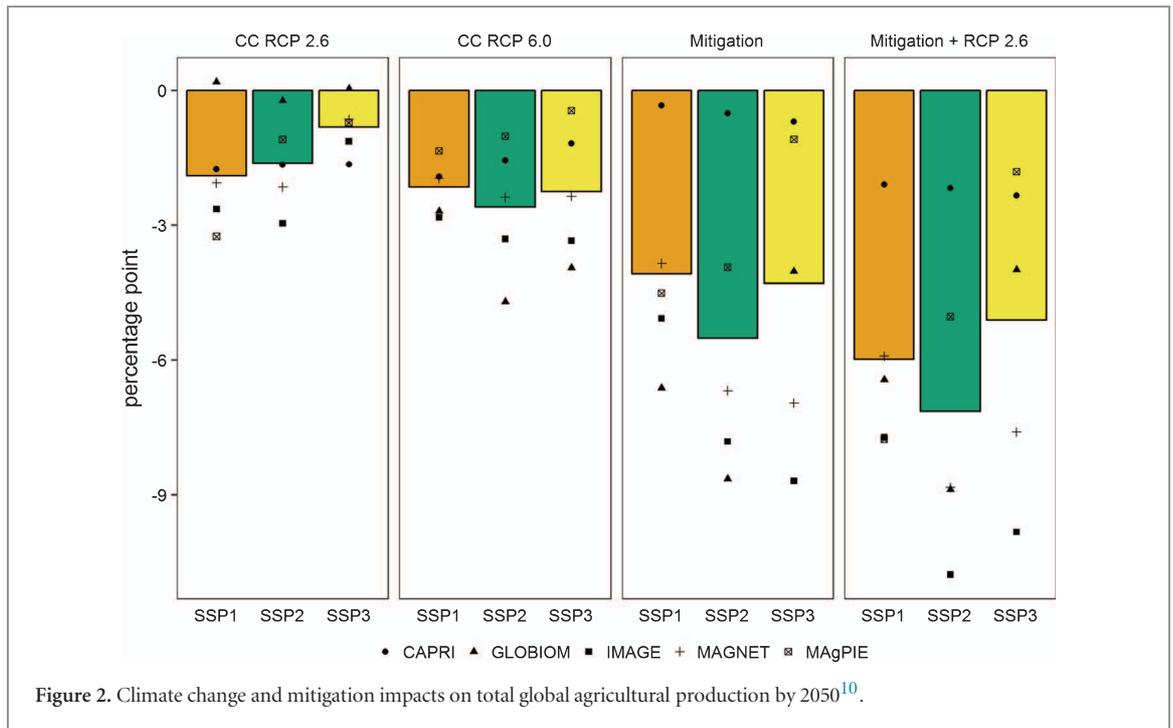
In CAPRI, the decline in agricultural non-CO<sub>2</sub> emissions is similar to the decline in IMAGE and MAGPIE as the same reference (Taylor *et al* 2012) has been used for mitigation effects in non-European regions. CAPRI has a quite detailed non-CO<sub>2</sub> mitigation modelling for Europe, but the global results are dominated by other regions. CO<sub>2</sub> emissions from land use change (LUC) are strongly decreasing in most mitigation scenarios and in some scenarios even become negative (notably SSP1) due to avoided deforestation (REDD), and afforestation (IMAGE and MAGPIE). As this indicator is not available from all the models, CO<sub>2</sub> emissions related to land use change CO<sub>2</sub> can be better indicated by the agricultural area expansion (see below).

### 3.2. Global agricultural production developments

In general, global agricultural production in SSP1 is less than in SSP2, which in turn is less than in SSP3 (see IMAGE, MAGNET and MAGPIE results in figure S.3.1). Following the SSP storylines and their implementation in the models, this indicates that the demand for agricultural products is more influenced by population developments and assumptions about waste and dietary preferences together than by assumptions on 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. In SSP3, MAGNET\IMAGE assume additional changes from 2020–2050, including a 33% waste and food losses increase, 20% higher meat consumption and 10% higher food import taxes, which increase demand and therefore also agricultural production. Also MAGPIE assumes that waste and food losses and livestock

consumption for a given per-capita income are higher in SSP3 and lower in SSP1, relative to SSP2. These features are less pronounced in GLOBIOM, which only considers a slower reduction in waste and food losses compared to SSP2 and SSP1. In this paper the further emphasis is not on the SSP results as they are dealt with in other papers (e.g. Nelson *et al* 2013, Popp *et al* 2017) and we focus on the climate and mitigation impacts using the four comparisons identified in section 2.2.

Figure 2 shows that the impact of climate change RCP6.0 and RCP2.6 on global agricultural production (primary crop and livestock) is negative with a range of 0.5%–2.5%. The impact is only slightly higher in RCP6.0 than RCP2.6, which is due to the selection of median scenarios as they actually imply rather similar yield impacts of the two RCPs by 2050. The ‘Mitigation’ column shows that in all SSPs and all models the mitigation measures result in negative impacts on global agricultural production that are larger than the negative climate change impacts. The combined effect of mitigation costs and climate change effects as shown in the ‘Mitigation + RCP2.6’ column is more negative on agricultural production than the no-mitigation scenario ‘CC RCP 6.0’. The gain in reduced negative climate impacts of RCP2.6 compared to RCP6.0 (compare first two columns) is too small to compensate for the negative impact of the mitigation measures. While from the literature it can be expected that RCP2.6 is more favorable for agricultural production than RCP6.0 in the long run beyond 2050 (Rosenzweig *et al* 2014), this does not hold in this study as radiative forcing in 2050 is quite similar. The selection process to identify a representative scenario of biophysical crop yield shocks is based on the globally aggregated change in yields. However, GCM projections



can differ substantially, especially in the spatial patterns of climate change (McSweeney and Jones 2016) and also GGCMs differ in their response to individual drivers and the represented agricultural system (Folberth *et al* 2016). For simulations of land-use changes under two cases of similar radiative forcing (RCPs in 2050), the spatial configuration of climate change impacts may thus be quite prominent in overall results. The spatial pattern of projected changes has not been considered in the selection of the median impact scenarios, which were selected on globally aggregated yield changes. Even if we had covered a large number of crop yield simulations with our economic model ensemble, it is very likely that the effects and their uncertainty bands in 2050 would have been similar. Our selection of SSPxRCP and GGCM combinations may have contributed to the finding that the costs of agricultural GHG mitigation under ‘Mitigation + RCP2.6’ are dominating over any climate related benefits for agricultural production compared to the pure climate change scenario ‘CC RCP6.0’ by 2050. It is very likely that this comparison would change later in the century.

In general, the additional cost of agricultural mitigation measures reduces production, most notably for rice and especially ruminant meat, in most models, which can be explained by the high GHG intensity of these two products. For most models the production of non-ruminants also decreases except for CAPRI, which observes an increase in production of some commodities (dairy and non-ruminants)

as consumers shift from the more GHG intensive ruminant meat to non-ruminant meat. 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. Cross price elasticities vary significantly in the literature, and there are few comprehensive studies available. Therefore, these are adjusted within CAPRI and MAGNET to calibrate the demand system. In MAGNET the elasticities are not implemented directly in the model but used in the calibration process of the CDE (constant differences in elasticities) demand parameters (see Woltjer *et al* 2014).

### 3.3. Land use

Cropland area generally increases when moving from SSP1 over SSP2 to SSP3 (figure S.3.2). This is due to higher demand for land due to the higher production levels (as described in 3.1), lower exogenous yields (as these are GDP-dependent and GDP declines from SSP1 over SSP2 to SSP3), and a low endogenous response of yields. In the case of MagPIE, also climate unrelated land protection policies explain differences between the SSPs. Climate change impacts (RCP2.6 and RCP6.0) increase cropland area in IMAGE\MAGNET, MagPIE and CAPRI, whereas cropland area decrease in GLOBIOM. For the former four models lower crop yields (see, table A1) and an inelastic food demand induce the higher land use. For GLOBIOM the negative impact on cropland is because grassland is relatively favored 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 (Havlík *et al* 2015b).

<sup>10</sup> Symbols represent the value for total global agricultural production which is the total of all primary crop and livestock sectors within a model. The bars represent the mean value across models.

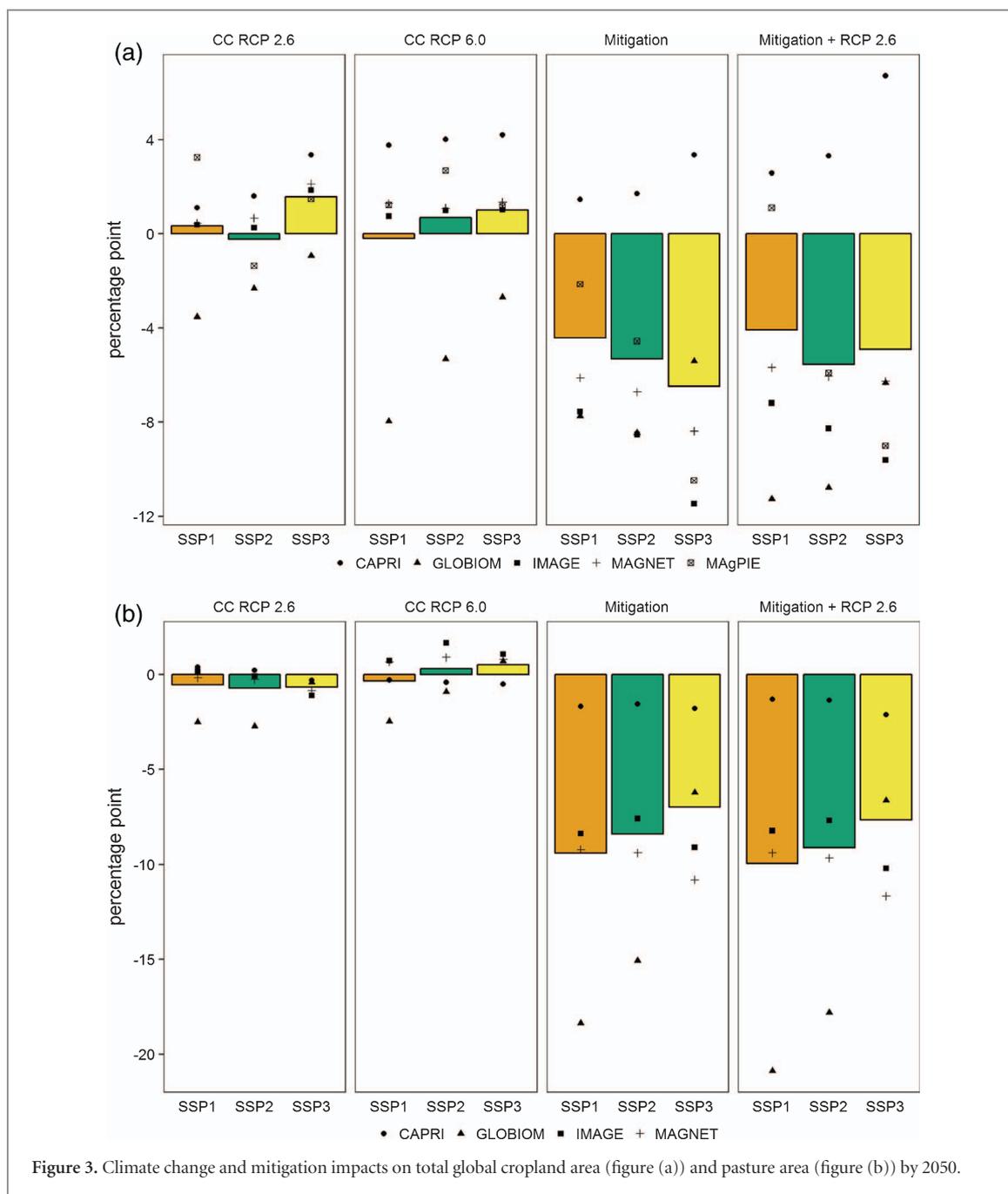


Figure 3. Climate change and mitigation impacts on total global cropland area (figure (a)) and pasture area (figure (b)) by 2050.

In all models except CAPRI, cropland area (i.e. land used for non-energy crops) decreases about 4%–7% due to mitigation measures (part (a) of figure 3). The decrease is caused by less available cropland due to avoided deforestation or afforestation and demand for bioenergy. In CAPRI, GHG mitigation was exclusively achieved by non-CO<sub>2</sub> emissions and especially decreased ruminant production, which released grassland and allows for a limited expansion of cropland.

Mitigation measures, in particular carbon price and bioenergy expansion, result in a decrease of about 7%–10% in grazing area in the GLOBIOM, IMAGE

and MAGNET models (part (b) of figure 3). Grassland decreases more than cropland, because land is allocated (with imperfect substitution) according to its rental price: cultivating crops gives higher returns to land than ruminants as the latter are more GHG intensive. Therefore, the decrease in available land impacts more on the ruminant sector where in addition partial substitution of grass by grains is possible. In CAPRI this effect is not reflected as afforestation is not specifically considered. The decrease in SSP1 is higher in GLOBIOM due to the assumption of faster transition possibility from grass based ruminant systems to larger reliance on concentrate feeds.

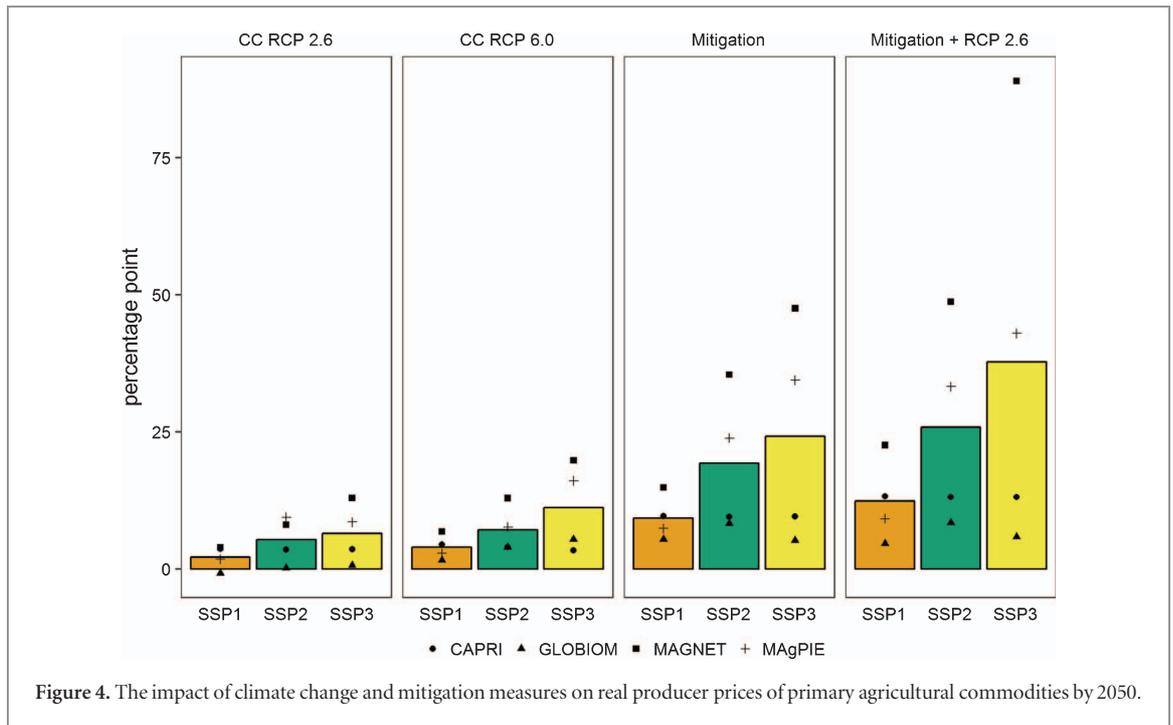


Figure 4. The impact of climate change and mitigation measures on real producer prices of primary agricultural commodities by 2050.

### 3.4. Producer prices

Compared to 2010, producer prices in real terms are lower in SSP1 in all scenarios, whereas they are stable or higher in SSP2 and further increase in SSP3 (figure S.3.4). Important drivers on the production side are lower yields in SSP3 than in SSP2 and SSP1. The lower prices in SSP1 are caused by supply side factors such as higher yields and higher labour productivity (MAGNET), which increase supply, in combination with demand side factors that lower demand such as lower food waste and less meat consumption. Price changes are rather small in GLOBIOM and CAPRI, intermediate in MAGPIE and rather big in MAGNET. In MAGPIE, producer prices are higher in SSP3 due to increased production costs as a result of a much higher population, more restricted trade and augmented costs for additional technological change. The higher price effects in the MAGNET model can mainly be explained by lower labor productivity growth, driven by lower GDP growth in SSP2 and especially SSP3 than in SSP1. As labor costs have a substantial share in total agricultural production costs, the labor productivity effect together with the yield effect imply that production costs are much lower in SSP1 than in SSP2, and much higher in SSP3. In addition to the labor productivity effect also land prices are an important driver of producer prices in MAGNET (van Meijl *et al* 2006).

Figure 4 shows that climate change increases agricultural producer prices in almost all cases due to lower crop yields that restrict supply, which also leads to increased feeding costs for livestock production.

The climate change impacts are more pronounced in MAGPIE and MAGNET. 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 a rapid increase in land prices. Additionally, the price-inelastic demand in MAGPIE does not buffer food prices.

Mitigation efforts lead to a higher increase in agricultural prices than the climate change effect by 2050. For crop prices the impact is more pronounced in MAGNET and MAGPIE than in CAPRI and GLOBIOM. As implemented 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. As implemented 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 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<sub>2</sub> emission taxes and completely inelastic food demand leads to increasing crop prices in the mitigation scenarios. Regarding livestock producer prices, mitigation measures lead to higher price increases for livestock products than for crops, because livestock is more emission intensive and emission taxes, therefore, increase livestock production costs relatively more than crop production cost.

#### 4. Discussion and conclusions

For this paper, common scenarios on climate change and mitigation options were assessed with five agro-economic models. Model inputs were harmonized by using the same projections for population and GDP growth, SSP narratives, as well as relative biophysical crop yield changes due to climate change. Scenario results are relatively consistent across SSPs (SSP1, SSP2 and SSP3) and climate scenarios (RCP2.6 and RCP6.0 with and without mitigation policies in place), despite the fact of using models with some significant structural differences. The overall trends of the 12 scenarios are very similar and the few 'outliers' can be explained by structural model characteristics or different scenario implementation choices. The scenario results highlight vulnerabilities, changes in production, area and price effects in the global agricultural sector. In most models global agricultural production is lowest in SSP1 and highest in SSP3, which indicates that the demand for agricultural products is more influenced by the SSP-related assumptions on changes in population, waste and food losses, and dietary preferences than by the assumptions on GDP developments. So far as median assumptions on yield shocks are taken, the impact of climate change on agricultural production by 2050 is negative but relatively small at the aggregated global level. The impact is fairly similar between the two CO<sub>2</sub> concentration pathways RCP6.0 and RCP2.6 as the radiative forcing in 2050 and therefore yield impacts are similar. In contrast, as crop model results have shown, climate impacts will increasingly differ between RCP2.6 and RCP6.0 after 2050. In addition, GCMs are typically capable to reproduce interannual yield variability in regions with high inputs and stable management conditions, but currently cannot account for other sources of yield variability such as pests and diseases that may also respond to climate change, ozone damage, or direct heat stress (Müller *et al* 2017). Climate change impacts are projected to become more severe in the second half of the 21st century. For instance, Porter *et al* 2014 found that while only about 2% of available climate change impact projections for crop yield foresee a drop in yields by more than 50% for the period 2050–2069, almost 20% of the projections foresee such a strong decline in yields for the period 2090–2109. The negative effects of climate change can also be underestimated because only the trend in climate change impacts has been considered ignoring the likely increase in extreme weather events. Although it is projected that the negative effects of climate change will increase over time, our conclusions that the effect on agriculture of mitigation is stronger would probably hold even if moving the time horizon to 2080

and considering the strong climate change scenario RCP8p5. These conclusions are consistent with Havlík *et al* (2015a) who considered such scenarios in a single model framework. However, the purpose of our study is not to evaluate the full costs and benefits of climate change mitigation over the long term but rather to highlight potential challenges related to it in the medium term.

The modelled GHG emission mitigation measures 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 due to the limited impact of the climate change scenarios by 2050. Our analysis finds that a mitigation strategy that takes into account residual climate change effects (Mitigation + RCP2.6) has a negative impact on agricultural production relative to a no-mitigation strategy and stronger climate impacts (CC RCP6.0). In line with the production results, by 2050 climate impacts 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 is mainly due to differences in the general model set-up (especially treatment of technological change and price responsiveness of demand) and assumptions on mitigation measures (e.g. carbon pricing). This analysis is a further step towards a better understanding of economic impacts of climate change and mitigation on the global agricultural sector and how they are reflected in the agro-economic models. The agro-economic models used in this study show shortcomings that should be improved for future research, especially regarding sound cross-price elasticities (all models), endogenous demand systems (MAGPIE) and an endogenous approach for the process of technological change. 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 to be done to increase consistency for a better comparison of model results. Moreover, we only present results at the global level, and further research is needed to identify vulnerabilities, adaptation and mitigation strategies for regional agricultural sectors.

**Disclaimer:** The views expressed are purely those of the authors and may not in any circumstances be regarded as stating an official position of the European Commission or the other institutions involved.

## Annex

Table A.1. Mapping of climate yield impacts from crops in the three crop models to the 24 commodity classes.

Agricultural commodity (acronym)	EPIC HadGEM2-ES	EPIC for all 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).

Table A.2. Regionally aggregated climate change impacts using the SPAM (You *et al* 2010) crop production area data (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

Table A.3. CH<sub>4</sub> and N<sub>2</sub>O related emission sources and mitigation measures included in the models.

CH <sub>4</sub> 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?
CH <sub>4</sub> emissions from on-field burning of agricultural waste	CH <sub>4</sub> emissions from on-field burning of agricultural waste including stubble, straw, etc. (IPCC category 4F)	no	no	From FAOSTAT, kept constant	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
CH <sub>4</sub> 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
CH <sub>4</sub> 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
CH <sub>4</sub> 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

Table A.3. Continued.

CH <sub>4</sub> 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?
CH <sub>4</sub> emissions from on-field burning of agricultural waste	no	no	no	no	no	no	no	no	no
CH <sub>4</sub> emissions from Animal waste management (AWM)	IMAGE model	yes, 1. MAC curve EPA and Lucas et al. 2007; 2. Emmission 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 emmissions and cost of abatement	CH4MAN, Efs per activity	AD	yes	CH4MAN, Efs per ton of product	via exogenous change in Efs	via exogeneous cost per ton
CH <sub>4</sub> emissions from enteric fermentation	IMAGE model	yes, 1. MAC curve EPA and Lucas et al. 2007; 2. Emmission 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 emmissions 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 exogeneous cost per ton
CH <sub>4</sub> emissions from rice production	IMAGE model	yes, 1. MAC curve EPA and Lucas et al. 2007; 2. Emmission 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 emmissions and cost of abatement	CH4RIC, Efs per activity	Rice measures	yes	CH4RIC, Efs per ton of product	via exogenous change in Efs	via exogeneous cost per ton

Table A.3. Continued.

N <sub>2</sub> O 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?
N <sub>2</sub> O emissions from agricultural waste burning	Anthropogenic N <sub>2</sub> O emissions from ag waste burning	no	no	From FAOSTAT, kept constant	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
Direct and indirect N <sub>2</sub> O 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 N <sub>2</sub> O 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 N <sub>2</sub> O emissions from fertilizer and manure spreading	yes, MAC curve EPA and Lucas et al. 2007	no, only via MAGNET
Direct and indirect N <sub>2</sub> O 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 N <sub>2</sub> O emissions from manure spreading and manure left during grazing		no, only via MAGNET

Table A.3. Continued.

N <sub>2</sub> O 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?
N <sub>2</sub> O emissions from agricultural waste burning	no	no	no	no	no	no	no	no	no
Direct and indirect N <sub>2</sub> O emissions from animal waste management (AWM)	IMAGE model	yes, 1. MAC curve EPA and Lucas et al. 2007; 2. Emmission 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 emmissions 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 exogeneous cost per ton
Direct and indirect N <sub>2</sub> O emissions from cropland soil fertilization (mineral fertilizer and manure application)	IMAGE model	yes, 1. MAC curve EPA and Lucas et al. 2007; 2. Emmission 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 emmissions 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 exogeneous cost per ton
Direct and indirect N <sub>2</sub> O emissions from manure excreted on pasture range and paddock	IMAGE model	yes, 1. MAC curve EPA and Lucas et al. 2007; 2. Emmission 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 emmissions 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 exogeneous cost per ton

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