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Why Do Global Long-term Scenarios for Agriculture Differ? An overview of the AgMIP Global Economic Model Intercomparison

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Abstract

Recent studies assessing plausible futures for agricultural markets and global food security have had contradictory outcomes. To advance our understanding of the sources of the differences, ten global economic models that produce long-term scenarios were asked to compare a reference scenario with alternate socio-economic, climate change and bioenergy scenarios using a common set of key drivers. Several key conclusions emerge from this exercise: First, for a comparison of scenario results to be meaningful, a careful analysis of the interpretation of the relevant model variables is essential. For instance, the use of ‘real world commodity prices’ differs widely across models, and comparing the prices without accounting for their different meanings can lead to misleading results. Second, results suggest that, once some key assumptions are harmonized, the variability in general trends across models declines but remains important. For example, given the common assumptions of the reference scenario, models show average annual rates of changes of real global producer prices for agricultural products on average ranging between -0.4% and +0.7% between the 2005 base year and 2050. This compares to an average decline of real agricultural prices of 4% p.a. between the 1960s and the 2000s. Several other common trends are shown, e.g. relating to key global growth areas for agricultural production and consumption. Third, differences in basic model parameters such as income and price elasticities, sometimes hidden in the way market behavior is modeled, result in significant differences in the details. Fourth, the analysis shows that agro-economic modelers aiming to inform the agricultural and development policy debate require better data and analysis on both economic behavior and biophysical drivers. More interdisciplinary modeling efforts are required to cross-fertilize analyses at different scales.

Keywords: computable general equilibrium, partial equilibrium, meta-analysis, socio-economic pathway, climate change, bioenergy, land use, model intercomparison.

JEL Codes: C63, C68, Q11, Q16, Q24, Q42, Q54

Introduction

Long-term scenarios for global agriculture, food and the environment have become increasingly important for the public debate on agricultural priorities. Recent developments such as the sharp increase of agricultural and food prices in 2007/08, 2010 and, for a number of commodities, in 2012, and projections for persistently higher real commodity prices in the medium term when compared to the early 21st century (OECD/FAO 2013) give rise to concerns about the ability of the global food supply system to keep pace with increasing demand. Given the long time lags associated with developments that impact the future paths of agricultural markets, trade and the environment, the debate covers developments well beyond the coming decade. To help explore possible developments in the future and alternate strategies to influence these developments, scenarios – statements about the future of a system where complexity and uncertainty require more precise language than “likely” or “most plausible” developments (Zurek and Henrichs, 2007) – can provide alternate views of the pathways, and a tool to test policy strategies.

Recent studies assessing plausible futures for agricultural markets and global food security have had contradictory outcomes (e.g., Nelson et al., 2010, INRA-CIRAD, 2009, and van der Mensbrugghe et al., 2011). This variability arises from the interaction of differences in perspectives on future drivers, in the modeled responses of producers and consumers to those drivers, and in the way the results are reported. Because these scenarios are undertaken independently, with assumptions reported in technical annexes or not at all, it is difficult for decision makers to assess why the outcomes differ, and in particular to tell whether differences in the scenarios are due to differences in assumptions about key driving factors or to methodological differences in the modeling frameworks. For a brief overview on recent scenario studies concerned with the future of the global food system, see the Supplementary Information.

This paper gives an overview of an extensive scenario comparison exercise undertaken in the context of the Agricultural Model Intercomparison and Improvement Project (AgMIP, www.agmip.org), involving ten of the world’s leading global economic models (see below). The paper provides details on how the comparison was done, putting emphasis on steps taken to make the results of the various models actually comparable. It then reports selected results of the comparison, both from the reference scenario and the various counterfactual scenarios. A discussion of the main findings and a concluding section round out this paper. Other papers in this issue report on selected topics covered by the review.

Method of analysis

The model suite

A total of ten global multi-region multi-sector models ran a set of well-defined scenarios for 2030 and 2050. These include six computable general equilibrium (CGE) models and four partial equilibrium (PE) models (see Table 1). Both the spatial resolution and the level of disaggregation of the agricultural sector are very different across these models – both are functions of their histories and original purposes.

These models differ in a number of other characteristics, as shown in Table 1. For instance, half 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 most CGE models have a spatially explicit representation of bilateral trade flows using the Armington approach (except AIM which only represents net trade), while most PE models consider only net-trade to a spot world market (except GLOBIOM which represents bilateral trade flows).

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

Table 1 about here.

Scenarios analyzed

The goal of the model comparison exercise was to understand the differences in model projections and model behavior and to identify their sources; *not* to choose scenarios for their plausibility.

Great effort was made to harmonize the values of three sets of key drivers - socioeconomic (population and GDP growth), productivity assumptions for crop yields, energy price assumptions (based on the crude oil price), and, for two of the scenarios (S7 and S8, see below), assumptions on the production of biomass-based energy.[1]

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[1] Within CGE models, total factor productivity (TFP) growth rates across sectors are calibrated to the harmonized GDP growth rates and primary factor endowments. Details can be found in Robinson et al. (2013).

Scenarios were constructed from a common reference scenario (S1) by varying the drivers in one of three dimensions – socio-economic change (S2), climate change impacts (S3-S6), and bioenergy demand (S8) and comparing the results to the reference scenario (Table 2)[2].

Table 2 about here.

Making results comparable

A major step towards comparability of model results was the harmonization of output reporting, commodity groups analyzed, spatial aggregation, variable definitions, and periodicity.

For this analysis, the following eight groups of agricultural commodities are considered: wheat (WHT), coarse grains (CGR), rice (RIC), oilseeds (OSD), sugar (SUG), ruminant meat (RUM), non-ruminant meat (NRM), and dairy products (DRY). In addition, aggregates were calculated for the five crop aggregates (CR5), for all crops combined (CRP), and for all agriculture combined (AGR). A table with more details on the commodity coverage of this analysis can be found in the Supplementary Information (Table SI-4).

It should be noted that for some models, the boundaries of individual commodity groups could not be harmonized completely. In particular, other temperate cereals including rye, barley, triticale and oats are grouped together with wheat rather than coarse grains in MAgPIE, while GLOBIOM only includes sugar cane in the sugar aggregate.

In representing results, the world was broken down into 13 regions, including five individual countries (Canada – CAN, United States – USA, Brazil – BRA, China – CHN, India - IND) and nine country aggregates (Other South and Central America – OSA, Europe – EUR, Former Soviet Union – FSU, Middle-East and North Africa – MEN, Sub-Saharan Africa – SSA, South-East Asia – SEA, Other Asia – OSA, Australia and New Zealand – ANZ). A map showing this spatial resolution of the analysis

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[2] Specifically, S2-S6 are compared to S1, while S8 is compared to a modified reference scenario S7 which, unlike S1, applies common assumptions on bioenergy production.

can be found in the Supplementary Information (Figure SI-1). To accommodate differences in model disaggregation, several larger regional aggregates were also included.

However, the regional aggregates may differ from those in Figure SI-1 for individual models, depending on the models' original spatial aggregations. For instance, in MAgPIE, the ANZ region, defined for the rest of the models as Australia and New Zealand, also includes Japan as well as numerous Pacific Islands, and the China region (CHN) also includes Cambodia, Laos, Mongolia and Vietnam.

A widely used metric of agricultural performance is the 'world price'. While most PE models use one reference price of a key exporter or importer for each commodity (assuming that prices across regions largely move in parallel), CGE models using the Armington assumption calculate weighted averages of their regional producer or export prices. Each of these concepts has its own deficiencies, and depending on the relative shares in global production and exports these prices can develop quite differently. The concept used in this analysis that is most comparable across all the models is the producer price averaged across world production regions, weighted by output. In addition, we are interested in 'real prices', i.e. free of inflation. The choice of deflator can significantly affect the results, as discussed below. The deflator used in this analysis is the global GDP deflator.

All models reported results for the years 2030 and 2050 as indices relative to a 2005 base year. As models' base years differ, 'hypothetical' base year data for 2005 were calculated using the average annual growth rates between the actual model's base year and 2030 values.[3] It should be understood that the indices for 2030 and 2050 do not represent 'projected' values for these years specifically. Rather they indicate medium- and long-term scenario values describing how agricultural markets could, on average, develop within the next 20 and 40 years, respectively, under the scenario model assumptions.

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[3] MAGNET and FARM are exceptions to this rule as these models provide data for both 2004 and 2007. It is therefore data for these two years which were used to interpolate the hypothetical 2005 base year values.

Reviewing the results

This overview paper provides a ‘bird’s eye’ perspective on the results. The paper groups key results into five broad categories, emphasizing areas of agreement and differences (categorized as Type-1 to Type-4 differences) across models.

This paper also includes an econometric meta-analysis of the differences in price changes (both over time in the reference scenario, and between the reference scenario and alternative scenarios) as a function of model characteristics. Of particular interest is the generic distinction between CGE and PE models: we test the hypothesis that CGE models, due to their assumed larger degree of flexibility derived from the ability to allocate production factors to alternate sectors, dampen exogenous shocks (such as increased food demand due to population and income growth, or reduced agricultural production due to climate change), and hence have smaller price changes. In contrast, models that include bilateral trade flows based on either the Armington assumption (ENVISAGE, EPPA, FARM, GTEM and MAGNET) or on trade costs (GLOBIOM) assume more segmented global markets which could increase international price movements. We therefore test the hypothesis that these spatial-equilibrium models report larger price changes than net-trade models (AIM, GCAM, IMPACT and MAgPIE). To analyze the specific effects of model characteristics, we estimate fixed-effect models across model results for both 2030 and 2050, where price changes are used as dependent variables, while model characteristics are used as independent variables. We also control for the differences across commodities, by estimating commodity-specific constants.

Key results of the analysis

The reference scenario

For the reference scenario, economic assumptions, including on population and GDP growth, are based on the Shared Socio-economic Pathway (SSP) 2, corresponding to “middle of the road” projections largely following past trends and SSP3 characterized as “fragmentation” (see O’Neill et al., 2012, van Vuuren et al., 2012, and Kriegler et al., 2012, for a discussion of SSPs. The SSP data are available for download at IIASA/OECD, 2013[4]). In SSP2, global population reaches 9.3 billion by 2050, an increase of 35 percent from 2010. Population growth slows significantly over time and shows large differences across countries. Global GDP triples between 2010 and 2050, more rapidly during the first half of that period than after 2030. Growth in most OECD countries is assumed to be moderate, while GDP in a number of developing countries is assumed to grow more than 10-fold. Figure 1 provides a regional overview on assumptions for population and per capita GDP.

Figure 1 about here.

Apart from population and GDP, common assumptions were made on productivity growth rates for crops. The *intrinsic productivity rates* (IPRs) used within the IMPACT model (see Nelson et al., 2010, pp. 23ff. for details) were used as exogenous shifters in the reference scenario[5], which assumes no effects of climate change (see Figure 2). While the IPRs are used in PE models to shift the yield function, the shifters move the agricultural production function in CGE models such that it represents land-saving technical progress (see Robinson et al., 2013, for more details).

Figure 2 about here.

Focusing on comparability, the reference scenario (S1) assumes no climate change, a very restrictive assumption. Between 2005 and 2050, the S1 model results for the AGR aggregate price range from a decline of 15% to an increase of 39%, relative to the global GDP price index (Figure 3). As discussed above, ensuring comparability is of key importance to this exercise. However, as reflected in Table 1 above, the five CGE models almost all use different numeraires, i.e. prices relative to

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[4] A consortium of research institutes are developing a new set of scenarios for climate change research encompassing earth systems, crop and other specialized models and socio-economic scenarios. Currently there are three sets of so-called shared socio-economic pathways (SSPs), for each of five different storylines designated by SSP1 through SSP5. The three sets of SSPs have harmonized on a common set of five population scenarios developed at IIASA. The GDP scenarios have been developed by IIASA, OECD and PIK. For the purposes of the AgMIP exercise, all modeling teams have harmonized on the OECD GDP scenarios and the common set of population scenarios. The data have undergone a light transformation to make them broadly compatible for the various participating models.

[5] This exogenous productivity growth was added in all models to reflect technological change and other drivers exogenous to the system. In addition most models include an endogenous component to yields that allows adjustments to input and output prices. The exception is MAgPIE, which models technological change endogenously instead and hence does not use the exogenous productivity shifters.

which agricultural price changes are reported. To see the implications of basing results on different numeraires, Figure 3 shows price changes reported by CGE models both based on the model-specific numeraire and relative to a common one, the price index for the global GDP. As the figure shows, the choice of the numeraire in CGE models has significant implications for the prices reported. Throughout the rest of this paper, we will therefore discuss prices based on the common numeraire.

Figure 3 about here.

Even after harmonization of the numeraire, however, Figure 3 above still reveals a significant degree of variability in the price results across models. Indeed, the variability is little affected by this harmonization overall, despite the changes for individual models' results. In addition, the average prices shown in Figure 3 hide substantial variation across commodities, as discussed below. Before analyzing these differences in some more detail, however, it is instructive to compare them to historical price patterns. On average, real agricultural prices[6] have declined by some 4% p.a. between the 1960s and the 2000s. Average annual rates of change between the trended 2005 base year and 2050, as reported by the models, range between -0.4% and +0.7%. These results do not incorporate the negative productivity effects of climate change which, as we will see below, lead to greater prices increases. In other words, there is a clear agreement across models that, under the set of assumptions used for the reference scenario, the historical trend of falling prices is unlikely to continue over the coming decades, and that, compared to past developments, agricultural prices would remain fairly close to the levels seen during the 2000s.[7]

While there remain important differences across models concerning future price directions, these ranges are also much more narrowly defined than the range of results found in the literature - a

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[6] Price index of agricultural products (World Bank, 2013a), deflated by the global GDP inflation rate (World Bank, 2013b; for years preceding 1966, average GDP inflation rate for the USA, EU area, Japan, China, Canada and India, weighted by their 1960-1966 GDP in US Dollars – these six regions accounted for 80% for global GDP during that period).

[7] Note that climate change is likely to further increase agricultural prices, as discussed below.

consequence of substantial harmonization of assumptions and of reporting standards.[8] We look into the differences in scenario results in greater detail now.

Comparing price changes of crops to those of ruminant meat shows that the ten models can be divided into three groups of three to four each. For four models (the CGE ENVISAGE and the three PE models GCAM, IMPACT and GLOBIOM), the reference scenario has increasing livestock prices (+8% - +26% by 2050 for ruminant meat) but largely unchanged crop prices (-4% - +8%). Three models (MAGNET, EPPA and FARM) report falling prices for both crops and livestock products (although MAGNET expects prices for oilseeds and sugar to increase), while the remaining three models (GTEM, MAgPIE and AIM) report crop prices increasing by 30% and more – but ruminant price changes vary significantly (-11% - +25%).

Figure 4 about here.

The global averages hide much larger variations in regional producer prices, especially for the CGE models featuring an Armington trade specification that provides some degree of market insulation. The average price change for agricultural products in 2050, relative to the harmonized 2005 basis, in China ranges between +139% (AIM) and -41% (MAGNET). All models predict prices in India to increase, but the magnitude varies between 2% and 193%. Prices move much more symmetrically for partial equilibrium models due to the direct price transmission represented – an exception is MAgPIE. Because its trade shares are largely fixed based on historical data, MAgPIE has variations in changes of regional prices as large as most CGE models.

Price changes are related to significant differences in market developments. World agricultural production[9] increases by between 60% and 111% across models. Production growth is particularly strong for ruminant meat as well as for commodities used in the production of biofuels – sugar,

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[8] It is worth noting that the range of prices – even if still significant – has narrowed considerably since the project was initiated, resulting from both increased efforts in harmonizing basic assumptions and continued model improvements.

[9] Volume aggregates are calculated on the basis of base year prices with the exception of GCAM which calculated aggregates on a ton-by-ton basis.

coarse grains and oilseeds. In contrast, production and use of wheat and rice – key staple commodities in large parts of the world – tend to grow more slowly. Indeed, food use of agricultural products grows less significantly than total use, with rates towards 2050 between 43% and 99%.

Other key results largely common across models include the following:

- Africa and the Middle-East are relative hotspots for growth in agricultural consumption, while the increase in Europe is modest.
- Africa and Latin America have the largest gains in agricultural production, driven by the growth in their own markets and fuelled by above-average growth in agricultural land use and productivity.
- Despite the significant production growth over the coming decades, Africa and the Middle East, expand their net imports of agricultural products.
- North America and Oceania significantly expand their role as net food suppliers for import markets, particularly in crops.
- Brazil, too, increases net exports, in particular of meat.

As seen above, however, important differences across model results remain. These differences are caused by a variety of factors and will form important input to future work. Four types of differences in the modeling of long term developments in agricultural markets can be distinguished, and are briefly discussed next with specific examples from this comparison exercise.

A first category ("Type-1 differences") includes differences in model approaches or parameters where the existing literature suggests a more narrowly defined range could be achieved, without relying on substantial additional research. It has been shown, for instance, that agricultural commodities in general, and staple food commodities in particular, have income elasticities significantly lower than unity (Engel's law: the share of food in total expenditure decreases as income increases). Income elasticities for staples generally fall with rising incomes (see, e.g., Foresight, 2011, p. 51; Cirera and Masset, 2010; Gale and Huang, 2007), eventually becoming negative. Two of the CGE models, however, generally have increasing income elasticities over time, with some of the values, especially for staple crops, being much higher than suggested by the literature. While it needs to be noted that these parameters apply to direct household demand for the agricultural commodities only and hence exclude processed food, high income elasticities contribute to projections of strong growth in food demand and hence relatively high levels of agricultural prices. See Valin et al. (2013) for a more detailed discussion of food demand developments.

We also find that several models have price elasticities increasing (in absolute value) over time. In contrast, empirical research shows that demand for basic commodities such as food becomes less price elastic as incomes grow and the share of incomes spent for these basics becomes smaller (see e.g. Muhammad et al., 2011, pp. 14 ff.).

A second category ("Type-2 differences") refers to areas where more economic research and better economic data would likely narrow the differences between model outputs. For instance, current own price elasticities for non-ruminant meat in China range from -0.09 in AIM to -0.56 in GLOBIOM. Spreads for other commodities and regions are similarly large. More elastic demand implies that exogenous shocks are absorbed more by demand adjustments and hence result in smaller price changes.

Another Type-2 difference is that agricultural land use declines significantly both at the regional and global level for some models and increases in others. For instance, AIM reports a 45% decline in agricultural land use for China. The reason for the strong decline in China according to AIM is mainly driven by two factors: productivity growth together with slowing (and eventually negative) population growth allows for meeting demand with lower land use- At the same time, increasing labor costs pushes down land demand. The obvious question is to what degree agriculture in China (and elsewhere) could switch to less labor intensive production, i.e. substitute land and capital for labor as relative prices change. The issue also raises questions with respect to the sustainability of such changes from a rural development point of view.

Models also differ in their assumptions on the level of technical change for the other production factors, such as labor and capital, and the rate of technical change in agriculture versus the rest of the economy– a third example of a Type-2 difference. In CGE models labor, capital and intermediate inputs are key cost components and their development has a major impact on price developments. Technical change assumptions across production factors and sectors can strongly influence model results (see, Robinson et al., 2013). The consequences of these differences can be seen in the falling real prices reported by MAGNET, which models labor productivity growth in the agricultural sector endogenously and higher than in the rest of the economy that is dominated by the service sector.

The third category ("Type-3 differences") relates to areas of uncertainty where economists need better information from their colleagues from other disciplines, such as on biophysical relationships. An example of this kind of uncertainty is the large increase in land used for agricultural production reported for China (e.g. ENVISAGE: +21%), India (e.g. AIM: +31%) or South-East Asia (ENVISAGE and GCAM: +41% and +46%, respectively)[10]. These regions are known for their scarcity of land (see e.g. Alexandratos and Bruinsma, 2012), and more work is required to better understand whether these countries can increase significantly their agricultural land use in a sustainable way.[11]

More generally, however, we find a negative relationship between the expansion of global agricultural area and the average agricultural producer prices in 2050 – even though the results from EPPA and FARM fall somewhat outside this correlation (Figure 5). Such a relationship is not surprising per se, but it shows the importance of alternative representations of land use changes and reinforces the need for further research in land-use oriented disciplines to better and more narrowly

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[10] Note that the increase reported by the two CGE models AIM and ENVISAGE is an expansion in value terms at constant prices, and hence could partly reflect changes in the composition of land used. For instance, the conversion of (lower-value) pasture land into (higher-value) crop land would result in an increase of the land value reported by the models.

[11] Apart from the physical availability of land suitable for agricultural production, expansion will also depend on investments – either by domestic or foreign stakeholders – in both claiming and improving the virgin land and the required infrastructure. See e.g. Deininger and Byerlee (2011) for a review of related questions.

define future scenarios of land use and land conversion.[12] See Schmitz et al. (2013) for a detailed discussion of land use change in the various models.

Figure 5 about here.

Finally, a fourth category ("Type-4 differences") refers to areas of uncertainty that will not be resolved by research within the foreseeable future. Examples include GDP growth (and, more specifically, growth in disposable incomes), agricultural productivity changes, and climate change outcomes. Exploring the outcomes from a range of plausible drivers is essential, not least as these drivers in part depend on decisions on public policies and private investments.

Alternative socio-economic assumptions

To analyze the implications of alternate socio-economic assumptions across models, a first counter-factual scenario is based on population growth and GDP from the SSP3 scenario ("Fragmentation", see van Vuuren et al., 2012; O'Neill et al., 2012; Kriegler et al., 2012). When compared to the more middle-of-the-road SSP2 scenario, SSP3 implies higher population growth globally (+11% compared to SSP2) and in developing countries but lower population growth in the developed world. At the same time, economic output would be lower than under SSP2 virtually everywhere, with global GDP in 2050 more than 30% below its SSP2 level. Consequently, global per capita GDP falls by 39% relative to the reference scenario, with reductions by more than 50% in Sub-Saharan Africa and parts of Asia. In contrast, per capita GDP in Canada would be 10% higher (see Figure 2 above).

In this scenario S2, higher population growth for the less developed world means more mouths to feed, but lower per capita GDP growth tends to shift demand from higher-value meats and oils to staple grains. In consequence, total food consumption in developing countries could either increase or decrease compared to the reference scenario S1, depending on income elasticities of food demand. Across models that report it, global food calorie consumption per capita is 6-10% lower in

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[12] It is worth noting that the relationship between land use expansion and average prices is much less distinct when considering crops only, suggesting that the links between crop and livestock sectors are an important factor in determining agricultural developments.

S2 than S1, with Sub-Saharan Africa, and parts of Asia affected more negatively as per capita incomes are lower. Total consumption, in contrast, could go up or down due to higher population growth. In India, for instance, consumption of agricultural products is predicted by the CGEs ENVISAGE and FARM to be between 7% and 24% lower in 2050 compared to the reference scenario, whereas the models MAGNET and GCAM both predict a small increase in total agricultural use.

Consumers in developed countries, in contrast, consume more in S2 according to most models – although the results suggest changes in per capita food consumption relative to the reference scenario are moderate. Total consumption of agricultural products would decrease relative to the reference scenario in all developed regions and across models due to lower population growth.

Global consumption of agricultural products is simulated to fall relative to S1 by most models, albeit with varying magnitudes: For the agricultural aggregate, results range from barely any change (GCAM, GLOBIOM, IMPACT and AIM) to a 26% reduction (ENVISAGE). Consumption of livestock products is reduced more strongly than that of crops, consistent with the higher income elasticities generally found for meat and dairy products when compared to crops.

With reduced domestic use in developed regions in S2, most models have increased net exports relative to S1. This is particularly true for North America and Europe across most models. The positive effects for net exports by Australia/New Zealand are smaller but equally consistent across models. Net exports from Latin America decrease due either to higher domestic demand in most models or reduced supply following lower world prices as reported particularly by ENVISAGE (see below). Key importing regions such as North Africa / Middle East are found by most models to face higher net import requirements due to stronger domestic consumption.

The differences in the demand effects of S2 relative to S1 translate into substantial variation of price effects across models, with a weak link between stronger reductions in global consumption and lower prices relative to the reference scenario when compared across models. Two models (GCAM and GLOBIOM) show practically no impacts on world average producer prices in 2050 for the agricultural aggregate or for individual commodities. Both of them also show little change in global consumption (see Figure 6 – the picture for the five main crops is very similar). At the same time, two other models (IMPACT and AIM) reporting virtually no change in aggregate consumption show declining prices relative to the reference scenario. However, the models reporting the strongest decline in aggregate use, EPPA and ENVISAGE, also report strongly falling prices relative to the reference. FARM, MAgPIE and MAGNET, in contrast, have higher prices with slightly falling aggregate consumption. For MAgPIE and MAGNET, the higher prices result from endogenous adjustments to labor-saving technical change to account for the lower GDP and higher population growth rates in SSP3 compared to SSP2. One might expect prices for commodities with higher income elasticities to fall relative to those products with lower income elasticities. IMPACT results show this behavior with prices for rice (often an inferior good today and in particular with rising incomes) slightly higher but those for meat and dairy products falling by 15% and more relative to the reference. Other models do not show this as clearly, with many of them simulating prices for non-ruminant meat to increase relative to other commodities.

Figure 6 about here.

Climate change implications for long-term food security and agriculture[13]

This section reviews the model results for four climate change scenarios, all based on the Representative Concentration Pathways (RCPs) with the highest GHG emissions, RCP 8.5 (see Moss et al. 2010 for a discussion of RCPs). This RCP is used as an input into two general circulation models (GCMs) – IPSL-CM5A-LR (scenarios S3 and S5) and HadGEM2-ES (S4 and S6) (see Müller and Robertson, 2013, for more details). The resulting changes in regional temperature and precipitation were then used by two different crop models - LPJmL (S3 and S4) and DSSAT (S5 and S6) (see Müller and Robertson, 2013, for a detailed discussion of this process) which produced climate change related changes in average crop yields. All four climate change scenarios assume no fertilization

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[13] A more detailed discussion on the climate change scenarios can be found in Nelson et al. (2013).

effects of higher atmospheric contents of CO_2. It should be noted that a number of other factors through which climate change may affect agriculture and the general economy are also not accounted for, e.g. sea level changes, effects on energy demand, health and labor productivity. Climate change adaptation measures other than price-driven adjustments of supply and demand structures are also not taken into account. A more complete analysis of climate change impacts can be found e.g. in Roson and van der Mensbrugghe (2010).

Climate effects on biophysical productivity are negative in almost all cases, but differ widely across regions, commodities and scenarios. Globally, the scenarios using DSSAT results have greater yield declines for wheat, rice and especially coarse grains and sugar, whereas the yield shocks are more moderate on average for oilseeds, when compared to the two LPJmL scenarios. Differences between the two GCMs are generally more moderate overall, although they differ for individual regions and crops.

The productivity effects from climate change were used by each model to change yield determinants. In partial equilibrium models, the shocks were used as additive shifters in the yield or supply function, while CGE models implemented them as shifts in the land efficiency parameters of the production functions for agricultural sectors (see Robinson et al., 2013, for a more in-depth discussion on differences between CGE- and PE-approaches of modeling yield effects).

Results from most models suggest that climate change will generate higher prices for agricultural commodities in general, and for crops in particular, irrespective of the GCM and crop model used (Figure 7). As one would expect given the yield shocks, the two DSSAT scenarios (S5 and S6) generally show stronger price increases than the LPJmL ones (S3 and S4), with little difference between the GCMs, although for MAgPIE the two HadGEM2-ES scenarios (S4 and S6) show higher prices than the IPSL-CM5A-LR scenarios (S3 and S5). Prices increase for all crops with the exception of sugar in the two LPJmL scenarios where sugar yields increase. Price effects for the average of the five main crop aggregates range between a low +2% and a high +79% across models and scenarios.

Figure 7 about here.

As discussed in more detail by Nelson et al. (2013) and Schmitz et al. (2013), differences in the price effects of climate change are accompanied by differences in land use change. Globally, land used in 2050 for the five main crops changes due to climate change by between -2% and +26% across models and climate change scenarios. While one could expect to see a negative relationship between area expansion and price increase, no clear link can be found, suggesting that differences in the area expansion are not only a driver for, but also a result of differences in price changes across models.

Similar results can be found for the link between final yield changes (i.e., after both the climate change shock and the endogenous response to higher prices) and changes in crop prices. Like area changes, yield changes in the climate change scenarios differ widely across models, but a clear link between stronger yield reductions (i.e., smaller endogenous yield adjustments due to changed economics) and higher prices cannot be established. As in the case of area changes, differences in yield reductions are thus both cause and result of the differences in price changes across models. The same holds for adjustments in the use of crops.

Nonetheless, the implications of climate change for food consumption appear to be clear across models and climate change scenario: climate change reduces per capita calorie availability across the world, with only a few exceptions. The decline in per capita calorie availability is especially large for India: -11% in 2050 when compared to a no-climate-change reference.

Assuming no change in trade policies, we also find strong evidence that climate change could result in substantially higher net food imports. This is particularly true for India which is consistently – with the exception of EPPA – shown to increase its net imports for the five main crops. On the other hand, Canada and Brazil are shown by most models to increase net exports. Clearly for some regions trade will play an important role in adapting to increasing climate change. For other regions, results are more mixed (see Ahammad et al., 2013, for a more detailed discussion of trade in this comparison exercise).

Bioenergy: resource implications and agricultural markets[14]

A final set of scenarios, calculated only by a subset of five models (AIM, MAGNET, GCAM, GLOBIOM and MAgPIE), looks at the implications of substantially increased biomass use for energy purposes. The focus here is on second-generation bioenergy, based on cellulosic raw materials. Two counterfactuals are compared: first, the reference scenario is adjusted to harmonize on a zero second-generation biomass-based energy production assumption across the five models capable of running these scenarios. This is compared to a high-second-generation bioenergy scenario where global energy output from biomass-based energy output is increased to about 108 ExaJoule (EJ) in 2050, based on GCAM data. Biomass-based energy is assumed to be most significant – in absolute figures – in the Former Soviet Union (32 EJ), the USA (19 EJ), China (17 EJ), the Middle-East/North Africa region and in Europe (11 EJ each).

Depending on specific model implementations of bioenergy demand, the models differ with respect to the share of biomass coming from forest activities. In all models, some agricultural land is used for annual or perennial biomass production, thus reducing land available for crop production. In addition, the biomass production would compete for other resources otherwise used in the production of food and feed commodities.

In consequence, a substantial increase in bioenergy would, all else being unchanged, add upward pressure on agricultural prices, a result common to all the models. Most models suggest, however, that the average price effects for all commodities remain rather limited at less than 9% in 2050 (Figure 8). The exception is MAgPIE which predicts substantial price increasing impacts especially for ruminants, wheat, sugar and oilseeds. The much stronger increase in prices suggested by MAgPIE can partly be explained by the fact that the model treats the demand for agricultural products as

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[14] A more detailed discussion on the bioenergy analysis can be found in Lotze-Campen et al. (2013).

exogenous, thus limiting adjustments to the supply shock. In addition, MAgPIE assumes all biomass for energy to come from specific bioenergy crops, as opposed to other models which allow significant shares of the biomass to be provided from forest area or wastes of wood and crop residues. The five models also differ in the available area for agricultural land expansion. A more detailed discussion of the bioenergy scenarios can be found in Lotze-Campen et al. (2013).

Figure 8 about here.

Do PEs differ from CGEs? An econometric meta-analysis of model results

As indicated above, we undertake an econometric meta-analysis to analyze whether world price changes in the reference scenario between the 2005 base year and the 2030 and 2050 simulation years differ systematically by model type. In particular, we test the hypothesis that model types (CGE versus PE models) and the representation of bilateral trade flows (i.e. spatial-equilibrium models versus non-spatial equilibrium models[15]) systematically impact the simulated price changes. Using a fixed-effects approach, we estimate the following set of equations (1):

$$XRPR_{m,i}^{t} - 1 = a_i^t + b_{c(m)} + \varepsilon_{m,i}^{t} \qquad (1)$$

where $XRPR_{m,i}^{t}$ is the price index of commodity *i* in period *t* (2005** = 1) as simulated by model *m*, a_i^t is the estimated commodity specific constant, $b_{c(m)}$ is the estimated fixed effect of characteristic *c* of model *m*, and $\varepsilon_{m,i}^{t}$ is the error term.

Similarly, we analyze world price changes for the socio-economic (S2) and climate change shocks (S3-S6) relative to the reference scenario S1, and for the bioenergy scenario S8 relative to the adjusted reference scenario S7. We test the same hypotheses as for the reference scenario itself. The corresponding set of equations is:

$$rXRPR_{m,i}^{t} = a_i^t + b_{c(m)} + \varepsilon_{m,i}^{t} \qquad (2)$$

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[15] Models with a spatially explicit representation of bilateral trade flows include most CGE models (except AIM) via an Armington approach, as well as GLOBIOM, one of the four PE models, applying a Takayama-Judge approach.

where $rXRPR_{m,i}^{t}$ is the relative price change for commodity *i* in period *t* between the reference scenario S1 and the SSP3 scenario S2 as simulated by model m, a_i^t is the estimated commodity specific constant, $b_{c(m)}$ is the estimated fixed effect of characteristic *c* of model m, and $\varepsilon_{m,i}^{t}$ is the error term.

The estimated coefficients for the model characteristics b, together with their respective p-values, are reported in Table 4 below. The full estimation output can be found in the Supplementary Information.

For price projections in the **reference scenario** (which, on average, show increasing price changes), there appears to be a systematic difference in price changes between PE models on the one hand, and CGE models on the other, in that CGE systems tend to simulate lower prices than PE models. This result thus gives some support for the original hypothesis that CGE models generally allow for greater degrees of substitution within the production and demand systems, thus increasing the likelihood that market responses dampen price changes due to exogenous shocks, such as increased demand from population and income growth (see Robinson et al., 2013, for a more detailed discussion of the differences between CGE and PE models and qualifications of this hypothesis).

The spatial explicitness of bilateral trade flows represented in several models also tends to result in smaller price increases – a result that requires further research as it seems to contradict the original hypothesis of dampened prices due to more segmented markets in these models. All these effects are noticeable for both the medium-term (2030) and the longer term (2050), and are statistically significant at the 1%-level for both years (with the exception of the CGE estimate in 2050 which is significant only at the 5%-level).

We find an equally clear and statistically significant difference in the impact of the **SSP3 scenario** on world average producer prices between CGE and PE models. Compared to PE models, simulated price reductions across commodities are dampened on average by about 3 percentage points for CGE models when compared to PE models. Again, this dampening effect of CGEs on average prices can be explained by the higher substitution possibilities within their supply systems and more flexible demand.

We find a similar dampening effect on average price changes for models representing bilateral trade in a spatially explicit way. As for the reference scenario, this appears to contradict the hypothesis that these models, due to their inherently assumed more limited price transmission between domestic and international markets, would produce stronger price changes due to changes in agricultural demand.

The CGE models also tend to predict smaller price increases than PE models in the **climate change** scenarios relative to the reference scenario – a result that is statistically highly significant across all four climate-change scenarios and for both 2030 and 2050.

Reasons for this may be two-fold: first, and similar to the results for the socio-economic scenario above this result could confirm the hypothesis that CGEs have built in a higher degree of flexibility in the production and demand systems as well as in the allocation of production factors within the agricultural sector. With more flexibility, the production shock could be dampened through other or higher use of production inputs, or reduced demand, thus reducing the impact on output and markets. Second, however, this result may partly be the consequence of how the climate change shock is applied in CGEs when compared to the PE models. See Robinson et al. (2013) for a discussion of how the yield shocks are applied in CGE and PE models, respectively.

The fixed-effect results for models with a spatially explicit representation of bilateral trade flows (which include ENVISAGE, FARM, GTEM, MAGNET and GLOBIOM)[16] tend to produce stronger price increases due to the climate shocks – although this result does not hold for all cases. This result appears to support the original hypothesis of the lower price transmission resulting in stronger price changes following exogenous shocks. Given the contradictory results for the reference and SSP3

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[16] Note the significant overlap with the PE-CGE grouping, differing only in the two models AIM and GLOBIOM.

scenarios, however, such a conclusion seems to be premature. Additional research is required to better understand the implications of different trade representations on global simulation results.

Finally, we find a distinct difference between CGEs and PEs in the price effects of increased **bioenergy production**. Once again we find the dampening effects of CGEs, resulting in smaller price increases when compared to those reported by PE models. This effect is smaller and no longer holds for 2050 when the MAgPIE results are not included in the sample, however (see above).

We also find that models with a spatially explicit representation of bilateral trade flows (MAGNET and GLOBIOM) report lower price increases than the non-spatial trade models (AIM, GCAM and MAgPIE). This result appears inconsistent with expectations. As noted above, more work is required to understand the implications of modeling international trade differently.

The relatively small number of models participating in this analysis, and consequently the even smaller number of models featuring particular characteristics, forms an important caveat to this meta-analysis. This is particularly true for the bioenergy scenario, which uses data from only five models. Despite the statistical significance of most of the results, largely supportive of the postulated hypothesis notably for the difference between CGE and PE models, additional research is thus required to further clarify the links between alternative model types and scenario outcomes.

Table 3 about here.

Discussion

Despite the substantial differences the scenario results exhibit across models, the comparison of scenarios across a number of global economic models has revealed a number of largely common outcomes, including on relative hotspots for future growth in agricultural demand and production, the relative importance of productivity progress as compared to area expansions, and an increasingly important role for international trade. Such results, which appear fairly robust across the different scenarios simulated but to be the more significant, the more climate change will affect agricultural production, give preliminary indications that national and international policies as well as private investments will need to be prepared. Strong production growth will need to take place in a sustainable manner, as key growth regions feature large areas that are both environmentally sensitive and of global importance. The growth in domestic markets will furthermore require large investments to ensure that the infrastructure – from transport facilities to well-functioning market structures – keeps pace with requirements. With expanding trade in agriculture, investments in the necessary infrastructure is only part of the story: at least as importantly, further liberalization of international trade in agriculture will help to transfer food more easily and more efficiently from surplus to deficit regions.

Notwithstanding these general conclusions, a number of important differences across model results highlight the need for further research across various disciplines. A fundamental difficulty arises from estimating future demand over a long-term horizon. Most importantly, income growth needs to be translated into increased food consumption and changed consumption patterns. While Engel-curves provide some indication on how the relationship between income and consumption might develop, small differences in income elasticities add to substantial differences in projected food consumption. The comparison across the participating models suggests that the applied parameters – either explicit in the case of several PE models or implicitly embedded in the utility functions used to describe consumer behavior in the CGE models – vary significantly. More econometric research is required to better understand how consumers in different countries respond to rising incomes. The ranges of applied income elasticities, and some of their developments over time, give rise to concern. The existing body of literature provides guidance on how to narrow the range of parameters used in economic models, but no general consensus is found.

A second key area of uncertainty is the question to what degree – and at what speed – new land can be converted for agricultural use, how such a process might depend on the economic conditions, and to what degree such expansions might bring environmental and other social costs. Expanding into uncultivated – and often uninhabited – areas comes at considerable costs in terms of infrastructure, societal development and potential environmental pressures.

A better understanding of these linkages will require substantial research efforts on local possibilities, risks and costs. Some of this is economic research but the involvement of natural and social scientists or legal experts is essential. Full clarity is unlikely to be achieved on these questions, so this is a mixture of Type 2, Type 3 and Type 4 uncertainties requiring economic and other research as well as continued scenario approaches.

Several of the model results on agricultural land use appear to be noticeable. Along the process of comparing, criticizing and adjusting model results, a number of extremes could be eliminated. Within the data set used for this special issue, most area developments can be seen as fairly moderate. However, notable differences occur in the reporting of physical land areas. This is partly due to the fact that the CGE models are based on monetary units, and especially for land the translation into physical units is challenging.

Some results continue to raise questions: for several countries, subsets of models report substantial deviations of future agricultural land use from historical trends, e.g. strongly expanding land use in Canada or China, or shrinking land use in Brazil. Such results, too, require more analysis to better understand their underlying drivers and consultation with regional experts.

The third vast area of uncertainty is the accounting of technical progress in agricultural production. For PE models, this generally translates into assumptions about agricultural yield growth, thus ignoring the fact that some of that growth may come from increased use of other inputs, both variable and fixed. CGE models generally account for these different production factors, albeit at different levels of aggregation. Related to that, macro and sectoral total factor productivity (TFP) growth is another uncertainty. Evidence on the level of technical change for the other production factors, such as labor and capital, and the rate of technical change in agriculture versus the rest of the economy are far from conclusive. Assumptions differ widely among models[17] and are another

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[17] As noted above, productivity growth rates in CGE models are calibrated to match harmonized GDP growth assumptions. Robinson et al. (2013) discuss the different approaches across models in greater detail and show

important driver behind the different results. More empirical research is needed to open the black box of macro and sectoral technical change.

Looking across the various scenarios discussed in this paper, an additional important message seems to arise: The effects of alternate socioeconomic assumptions or assumptions on future growth in second-generation bioenergy, as simulated for this study, are small when compared to those arising from climate change (Figure 9). Both the climate change scenarios and the bioenergy scenario represent fairly strong differences relative to the reference scenario which represents a "middle-of-the-road world" (although the limitation of the bioenergy scenario to growth in second-generation biofuels excludes possible effects of first-generation biofuels which arguably have a much larger impact on agricultural markets on a per unit of energy basis; see e.g. OECD, 2008). On the other hand, the assumptions on population and GDP changes in the SSP3-scenario tend to impact markets in opposite directions, thus reducing its overall effects. It should also be noted that the climate change scenarios calculated here are based on a relatively small subset of existing GCMs and crop models and do not necessarily cover the spectrum of potential yield reductions resulting from climate change (for a wider representation of climate change effects see the work done by the Inter-Sectoral Impact Model Intercomparison Project ISI-MIP, www.isi-mip.org). Nonetheless, the comparison across the scenarios discussed in this paper suggests that climate change needs to be seen as a key variable in the discussion on future developments of agricultural markets and food securities, and the uncertainty around climate change and its implication for agricultural productivity represents a major obstacle in providing clear guidance on future agricultural pathways.

Figure 9 about here.

Conclusions

This paper has shown that a structured and consistent comparison of quantitative scenarios developed with the help of a large number of different global economic models provides an

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the sensitivity of results to alternative methods for distributing economy-wide TFP growth across sectors and primary factors, while for a recent review of work on agricultural productivity see e.g. Fuglie et al. (2012).

important input to the discussion about future developments in agricultural markets and food security. Harmonizing assumptions as well as reporting has helped to significantly narrow the spread of scenario outcomes in terms of agricultural prices and other key variables, highlighting the importance of assumptions and reporting on overall results. However, while the reporting principles defined for this comparison exercise were an important step for this work, individual models will continue to report in purpose-driven ways. Similarly, differences in key assumptions partly represent the uncertainty on major drivers for agricultural markets, and having harmonized key assumptions means that the results presented in this paper do not – and do not intent to – represent the full range of plausible outcomes. Indeed, the scenarios presented here and their underlying assumptions should be seen as quite restrictive.

That said, the results do provide strong indications on the relative importance of key driving forces for agricultural markets. They also show that, despite the harmonization of assumptions and reporting, important differences remain across the various models that have participated in the comparison, and that should not be viewed as covering the range of possible model outcomes.

The analysis has shown that principal differences can be found between results derived from CGE models and those produced with PE models. Indeed, and as postulated above, CGE models are found to report “smoother” price paths: lower price increases (or even decreases) in the reference scenario, and smaller price changes relative to alternative assumptions on exogenous drivers. With the strong caveat relative to the limited sample size in mind, this is an important outcome, but raises questions with regard to the approach that best reflects economic behavior and adjustment processes, or, more precisely, how the different modeling approaches can “learn” from each other. This comparison is an important step towards more exchange among modeling groups and a better informed dialogue about approaches, data and findings.

More work will be required in numerous areas, and this paper has discussed some of them without aiming to be exhaustive. Economic research will be important to better understand the adjustments made to changed prices and growing incomes by private households, but also by enterprises (including farms). Biophysical research – and increased efforts to combine biophysical with economic knowledge – will be crucial to better understand natural adjustment processes, such as potentials for future crop yields and their dependence on various climate variables. This also includes a better understanding on how factor intensities within agriculture are adjusted in response to developments in factor prices and productivities, and to climate change related shocks. Some areas of uncertainty will, however, remain for the foreseeable future, and scenarios will continue to represent an important tool for informing the debate about decisions for public policies and private investments.

To further improve the understanding of model differences, we also suggest doing controlled and straight-forward experiments on both the supply and the demand sides that would allow for the generation of comparable price elasticity matrices for area, yield and final demand across agricultural products. Finally, and in light of the importance scenarios can have for policies and investment decision, it will be necessary to bring decision makers and modeling groups closer to improve exchange and dialogue between them. This will help to define the scenarios most relevant for policies and investments, and allow decision takers to better understand the results and implications of the different models and scenarios – and to make best use of them.

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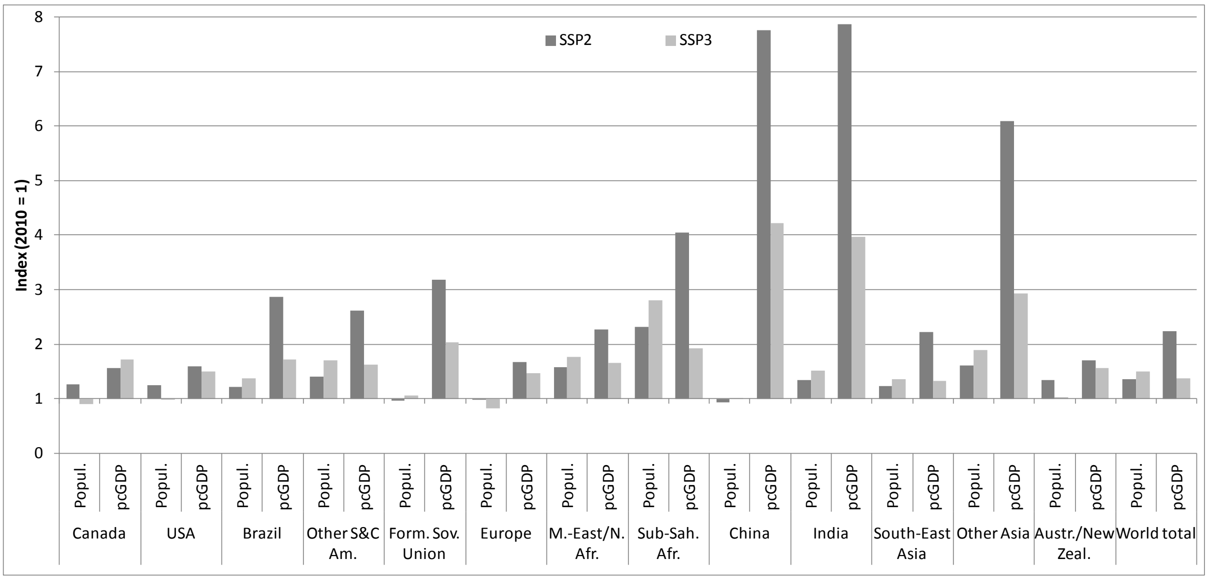
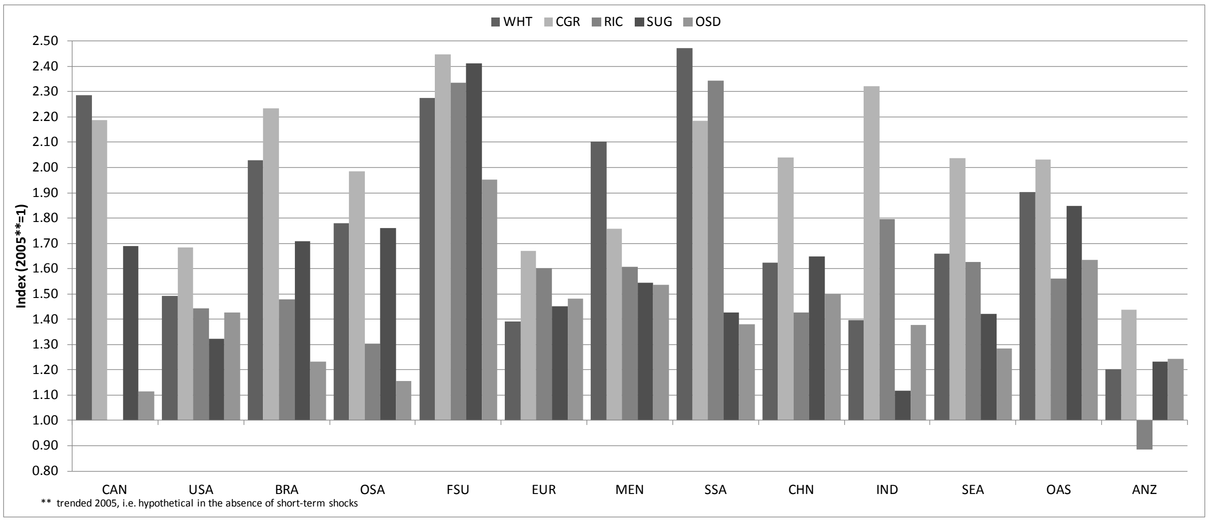
Figures and Tables

Figure 1: Population and per capita GDP growth to 2050 by region, SSP2 and SSP3



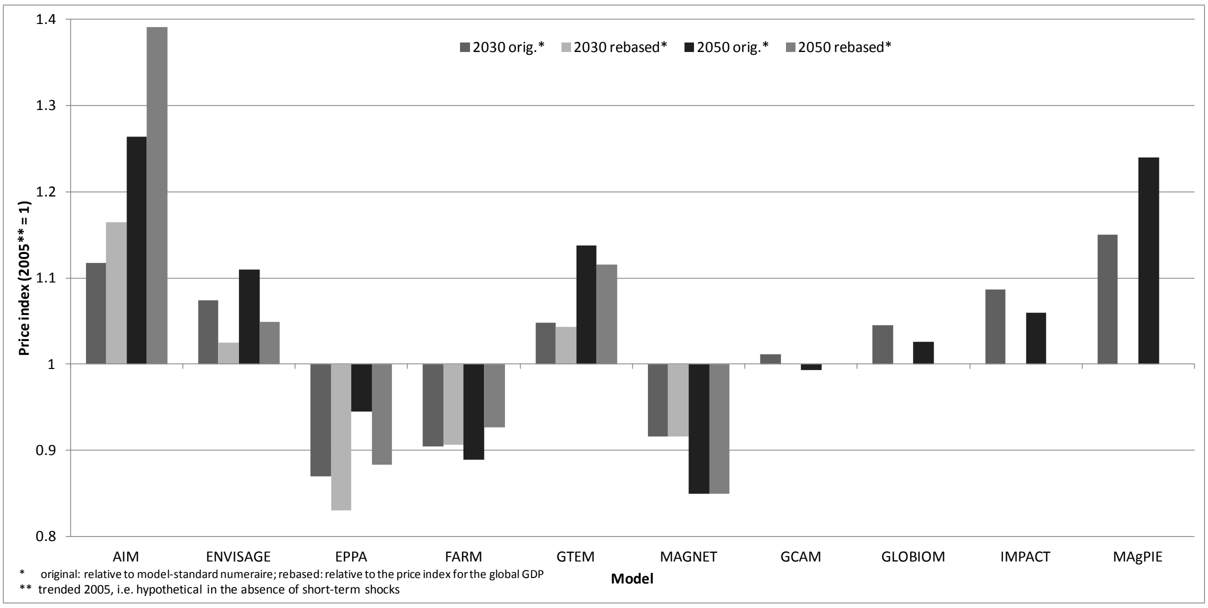
Source: modified from IIASA/OECD (2013)

Figure 2: Exogenous yield growth by region and crop, 2050 relative to 2005 base year



Source: IMPACT model output as of February 15, 2013.

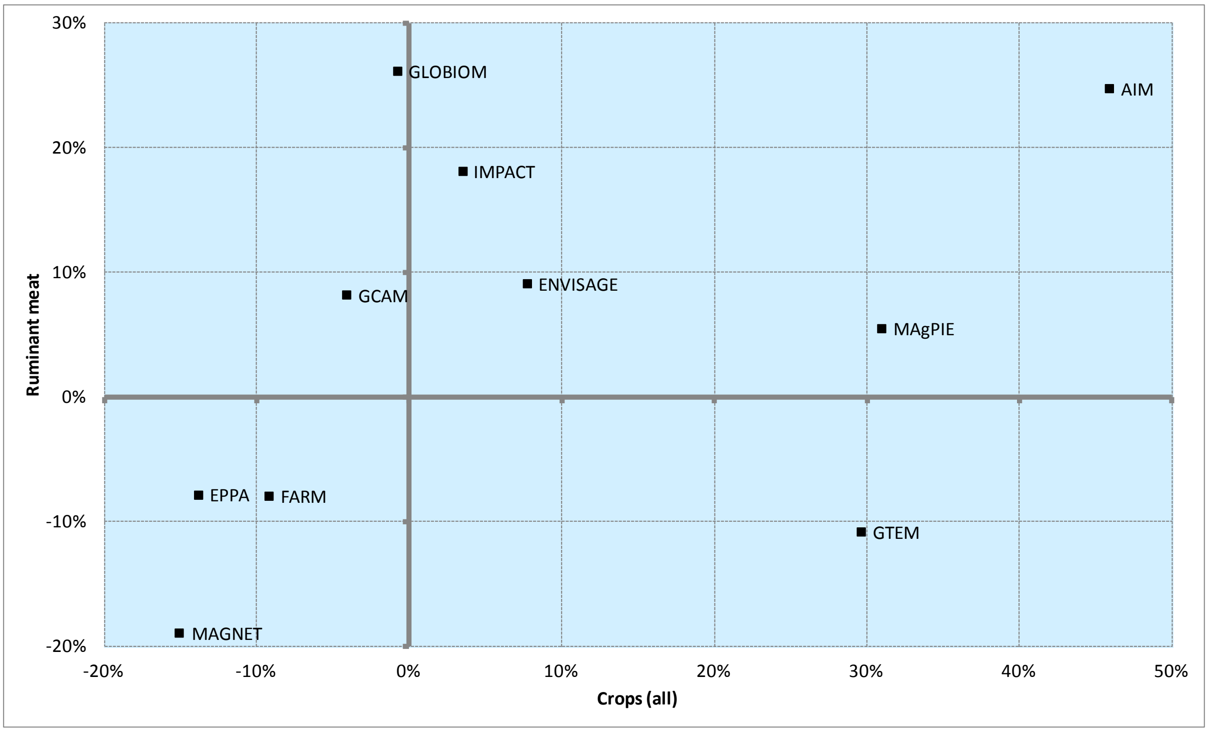
Figure 3: Price projections for the agricultural aggregate, 2005 - 2050**



Source: Model results as of February 15, 2013

Note: no rebasing for partial equilibrium models, nor for MAGNET which uses the price index of the global GDP by default.

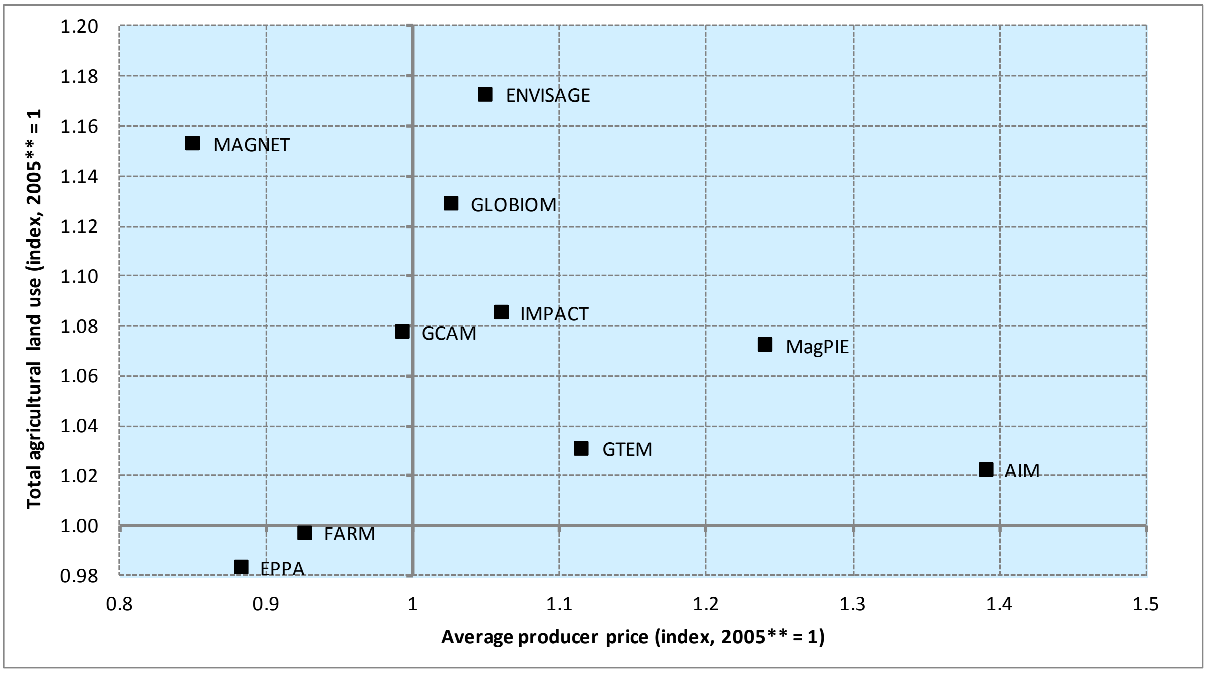
Figure 4: Crop versus ruminant prices in 2050 across models



Source: Model results as of February 15, 2013

Note: All price changes are relative to a “trended 2005”, i.e. the hypothetical base year data in the absence of short term shocks.

Figure 5: Agricultural area expansion versus average agricultural prices in 2050 across models

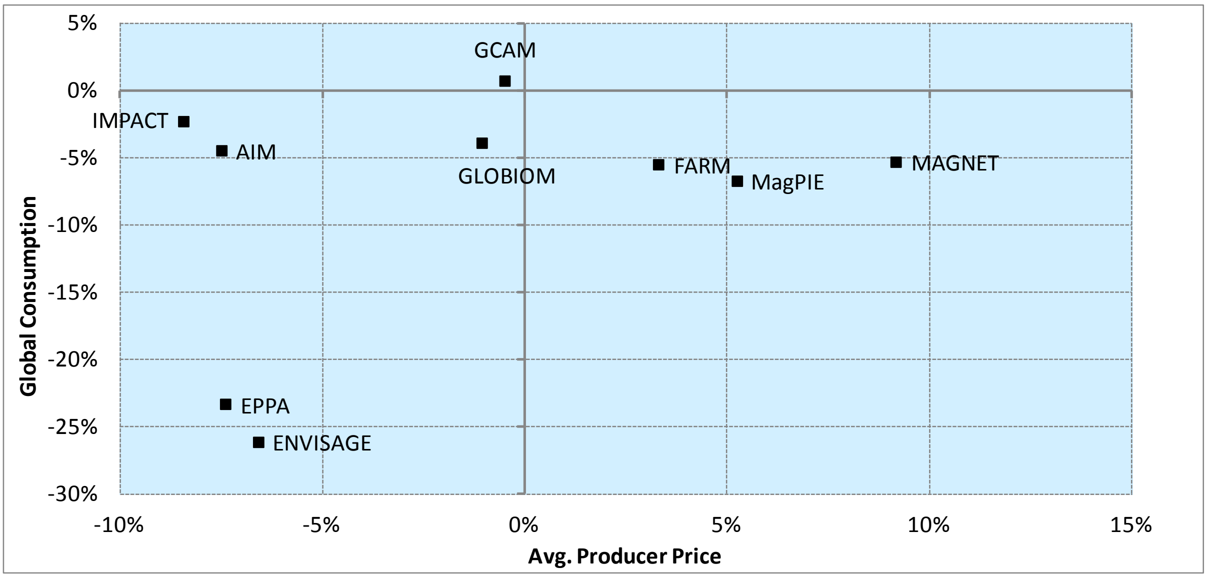


835

Source: Model results as of February 15, 2013

Note: All price and area changes are relative to a “trended 2005”, i.e. the hypothetical base year data in the absence of short term shocks.

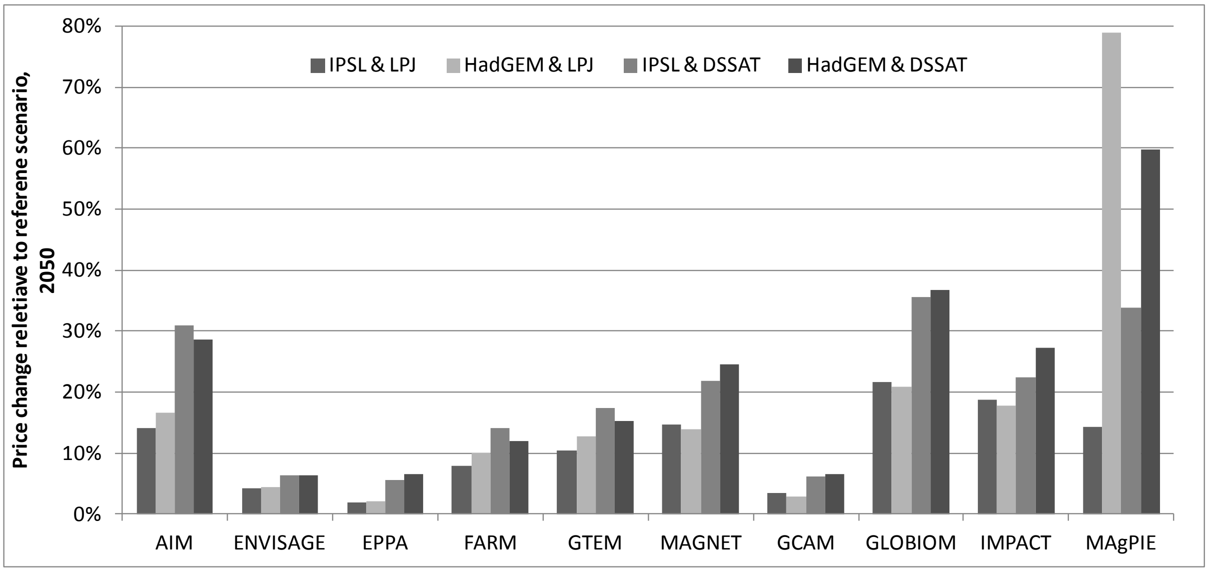
Figure 6: Changes in global consumption and average producer prices of agricultural products, SSP3 relative to SSP2, 2050



Source: Model results as of February 15, 2013

Note: All changes relative to the reference scenario for the same year. No aggregate consumption data available for GTEM.

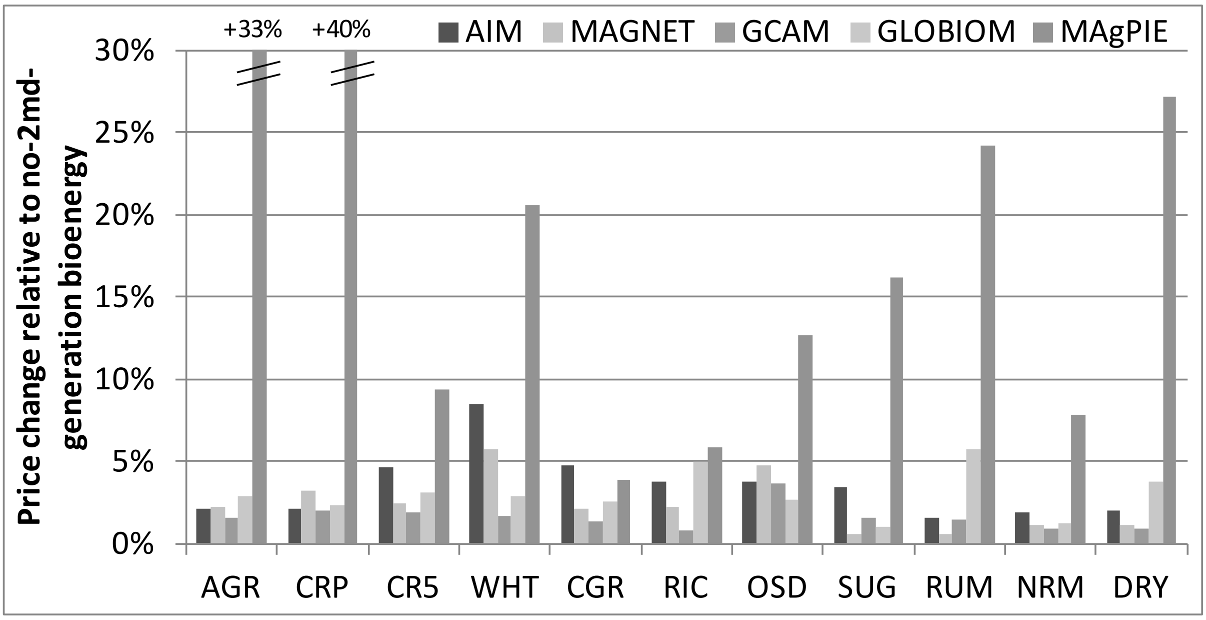
Figure 7: Changes in world average producer prices for five main crops (CR5) in 2050 due to climate change relative to no-climate-change



Source: Model results as of February 15, 2013

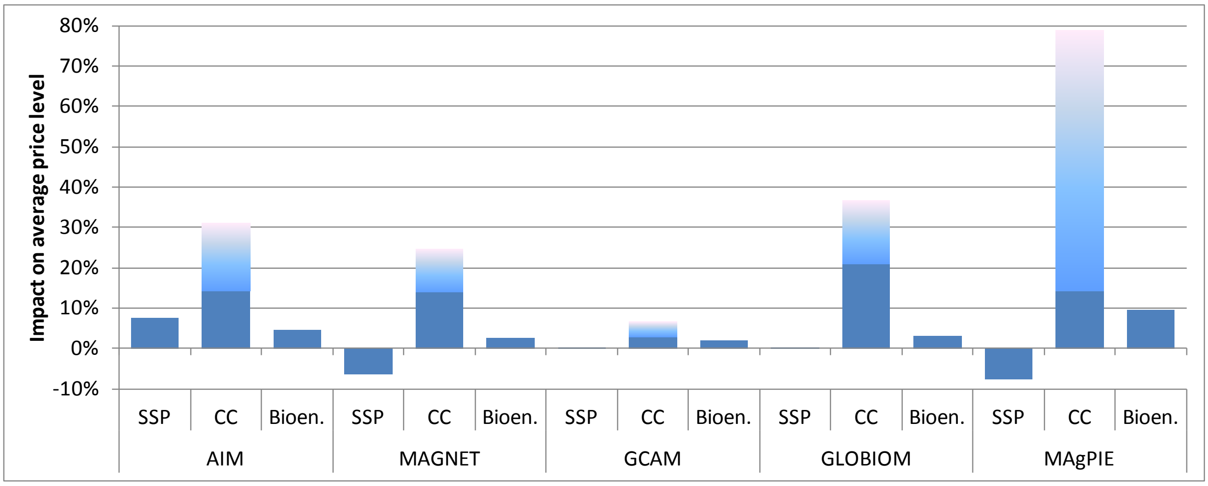
Note: All changes relative to the reference scenario for the same year.

Figure 8: Changes in world average producer prices due to second-generation bioenergy, 2050



Source: Model results as of February 15, 2013

Figure 9: Comparison of changes in world average producer prices due to alternative SSP assumptions, climate change and second-generation bioenergy, 2050



Source: Model results as of February 15, 2013

Notes: SSP refers to the effect of SSP2 relative to SSP3; CC refers to the effect of climate change relative to no climate change - shaded areas represent the range of price changes simulated for the different climate change scenarios; Bioen. refers to the effect of the production of 108EJ of energy from second-generation biomass.

Table 1: Key characteristics of participating models.

Model (References)	Institution	Type	Economy coverage	Agric. sectors*	Regions**	Base year	Agric. policies	Bioenergy	Global numeraire	Agric. supply	Final demand	Trade
AIM (Fujimori et al., 2012)	NIES, Japan	CGE	Full economy	8 / 1	89 / 17	2005	Implicitly assumed unchanged	Endogenous 1st and 2nd generation	US CPI	Nested CES	LES utility	Non-spatial; Armington gross-trade
ENVISAGE (van der Mens-brugghe, 2013)	FAO/World Bank	CGE	Full economy	10 / 5	11 / 9***	2007	Price wedges (based on GTAP)	None explicitly represented	High-inc. manuf'ed exports	Nested CES	LES utility (w/ dynamic shifters)	Armington spatial equilibrium
EPPA (Paltsev et al., 2005)	MIT, USA	CGE	Full economy	2 / 0	7 / 9	2004	Subsidies, taxes, tariff equivalents	Endogenous 1st and 2nd generation	US CPI	Nested CES	Nested CES utility	Armington spatial equilibrium
FARM (Sands et al., 2013)	USDA, USA	CGE	Full economy	12 / 8	5 / 8***	2004 (& 2009)	Price wedges (based on GTAP)	Little for electricity and heating	European Service Sector	Nested CES	LES utility	Armington spatial equilibrium
GTEM (Pant, 2007)	ABARE, Australia	CGE	Full economy	7 / 7	5 / 8***	2004	Implicitly assumed unchanged	Endogenous 1st generation	Capital goods	Nested Leontief and CES	CDE utility	Armington spatial equilibrium
MAGNET (Woltjer et al., 2011)	LEI-WUR, The Netherlands	CGE	Full economy	10 / 9	29 / 16	2001 (& 2004, 2007)	Price wedges (adjusted from GTAP); milk quotas	Endogenous 1st generation (incl. biofuel targets)	World GDP Deflator	Nested CES	CDE private demand**** and Cobb-Douglas utility	Armington spatial equilibrium
GCAM (Wise and Calvin, 2011)	PNNL, USA	PE	Agriculture, Energy	18 / 0	7 / 9***	2005	Implicitly assumed unchanged	Endogenous 1st and 2nd generation	n.a.	Leontief	Iso-elastic****	Heckscher-Ohlin non-spatial, net-trade
GLOBIOM (Havlik et al., 2013)	IIASA, Austria	PE	Agriculture, forestry, Bioenergy	31 / 6	10 / 20	2000	Implicitly assumed unchanged	Exogenous demand	n.a.	Leontief	Iso-elastic****	Enke-Samuelson-Takayama-Judge spatial equilibrium
IMPACT (Rosegrant et al., 2012)	IFPRI, USA	PE	Agriculture	32 / 14	101 / 14	2000	Price wedges (based on PSE/CSE)	Exogenous demand for feedstock crops	n.a.	Iso-elastic****	Iso-elastic****	Heckscher-Ohlin non-spatial, net-trade
MAgPIE (Lotze-Campen et al., 2008)	PIK, Germany	PE	Agriculture	21 / 0	0 / 10	2005	Implicitly assumed unchanged	Exogenous demand	n.a.	Leontief	exogenous	Based on historical self-sufficiency rates

Notes: * Figures indicate the number of raw and processed agricultural products represented, respectively; ** Figures indicate the number of individual countries and multi-country aggregates represented, respectively; *** Regional break-out specific for this application; **** Elasticities adjusted over time.

Table 2: Summary of scenarios analyzed in this project

Scenario code	**SSP**	**RCP**	**GCM**	**Crop model**	**Bioenergy**
S1	SSP2	Present climate	none	none	Model-specific
S2	**SSP3**	Present climate	none	none	Model-specific
S3	SSP2	**RCP8p5**	**IPSL-CM5A-LR**	**LPJmL**	Model-specific
S4	SSP2	**RCP8p5**	**HadGEM2-ES**	**LPJmL**	Model-specific
S5	SSP2	**RCP8p5**	**IPSL-CM5A-LR**	**DSSAT**	Model-specific
S6	SSP2	**RCP8p5**	**HadGEM2-ES**	**DSSAT**	Model-specific
S7	SSP2	Present climate	none	none	**1st-gen. ca. 6ExaJoule; no 2nd-gen. (2050)**
S8	SSP2	Present climate	none	none	**1st-gen. ca. 6ExaJoule; 2nd-gen. ca. 108EJ (2050)**

Table 3: Estimated effects of key model characteristics on world average producer price changes, 2005-2050 reference scenario and SSP3, climate change and bioenergy relative to the reference

Scenario	Model characteristics	2030		2050	
		coefficient	p-value	coefficient	p-value
S1 – Reference	**CGE**	-0.074	0.000	-0.052	0.049
	Spatial	-0.126	0.000	-0.221	0.000
S2 – SSP3 compared to S1	**CGE**	0.028	0.000	0.029	0.037
	Spatial	0.044	0.000	0.082	0.000
S3 – RCP 8.5 (IPSL-CM5A-LR / LPJmL) compared to S1	**CGE**	-0.052	0.000	-0.087	0.000
	Spatial	0.048	0.000	0.048	0.000
S4 – RCP 8.5 (HadGEM2-ES / LPJmL) compared to S1	**CGE**	-0.071	0.000	-0.129	0.000
	Spatial	0.014	0.068	-0.030	0.190
S5 – RCP 8.5 (IPSL-CM5A-LR / DSSAT) compared to S1	**CGE**	-0.122	0.000	-0.156	0.000
	Spatial	0.052	0.000	0.046	0.014
S6 – RCP 8.5 (HadGEM2-ES / DSSAT) compared to S1	**CGE**	-0.144	0.000	-0.213	0.000
	Spatial	0.038	0.001	0.029	0.221
S8 – High 2nd-gen. bioenergy compared to S7	**CGE**	-0.084	0.000	-0.033	0.004
	Spatial	-0.073	0.000	-0.033	0.004

Source: own fixed-effects estimation based on results of participating models, controlling for differences in commodities. For details and equations see text. The full estimation output can be found in the Supplementary Information.