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Climate change impacts on agriculture in 2050 under a range of plausible socioeconomic and emissions scenarios

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



Abstract

Previous studies have combined climate, crop and economic models to examine the impact of climate change on agricultural production and food security, but results have varied widely due to differences in models, scenarios and input data. Recent work has examined (and narrowed) these differences through systematic model intercomparison using a high-emissions pathway to highlight the differences. This paper extends that analysis to explore a range of plausible socioeconomic scenarios and emission pathways. Results from multiple climate and economic models are combined to examine the global and regional impacts of climate change on agricultural yields, area, production, consumption, prices and trade for coarse grains, rice, wheat, oilseeds and sugar crops to 2050. We find that climate impacts on global average yields, area, production and consumption are similar across shared socioeconomic pathways (SSP 1, 2 and 3, as we implement them based on population, income and productivity drivers), except when changes in trade policies are included. Impacts on trade and prices are higher for SSP 3 than SSP 2, and higher for SSP 2 than for SSP 1. Climate impacts for all variables are similar across low to moderate emissions pathways (RCP 4.5 and RCP 6.0), but increase for a higher emissions pathway (RCP 8.5). It is important to note that these global averages may hide regional variations. Projected reductions in agricultural yields due to climate change by 2050 are larger for some crops than those estimated for the past half century, but smaller than projected increases to 2050 due to rising demand and intrinsic productivity growth. Results illustrate the sensitivity of climate change impacts to differences in socioeconomic and emissions pathways. Yield impacts increase at high emissions levels and vary with changes in population, income and technology, but are reduced in all cases by endogenous changes in prices and other variables.

1. Introduction

Studies to date suggest that climate change has reduced growth in crop yields by 1–2 percent per decade over the past century, and adverse impacts are projected

to increase in the future (Gourdji *et al* 2013, Intergovernmental Panel on Climate Change (IPCC) 2014). But understanding the magnitude of these impacts is complicated by the interaction of numerous biophysical and socioeconomic factors.

Previous studies have combined climate, crop and economic models to examine the impact of climate change on agricultural production and food security, but results have varied widely due to differences in models, scenarios and input data (Rosenzweig and Parry 1994, Parry et al 2004, Nelson et al 2010).

Recent work as part of the agricultural model intercomparison and improvement project (AgMIP) has examined (and narrowed) these differences through systematic model intercomparison (Nelson et al 2014a, 2014b, von Lampe et al 2014). The explicit goal of that intercomparison of global economic models was ‘to understand the differences in model projections and model behavior and to identify their sources; not to choose scenarios for their plausibility’ (von Lampe et al 2014). Accordingly that exercise focused on climate impacts for a single high-emission representative concentration pathway (RCP 8.5), and a single ‘middle-of-the-road’ shared socioeconomic pathway (SSP 2). Running these scenarios with multiple climate, crop and economic models, they found global average yield reductions of 11 percent and price increases of 20 percent due to climate change relative to baseline values for major crops in 2050 (Nelson et al 2014a). However, these studies did not examine the impact of more plausible climate change scenarios, the sensitivity of the impact of climate change to different socioeconomic environments, or whether agricultural and trade policies could mitigate the impact on the agricultural sector and food prices by improving access to international supplies (Schmidhuber and Tubiello 2007).

This paper extends the literature by focusing on these three areas. As results are expected to differ widely between models, we use multiple models to obtain more robust results. Results from three general circulation models (GCMs) and five global economic models are used to examine the global and regional impacts of climate change on agricultural yields, area, production, prices and trade for coarse grains, rice, wheat, oilseeds and sugar (which together account for two thirds of global calorie availability and three quarters of harvested cropland area) to 2050. While climate change impacts are expected to increase more sharply after 2050 (Intergovernmental Panel on Climate Change (IPCC) 2014), an intermediate timeframe is critical for agricultural research and development planning that is currently under way.

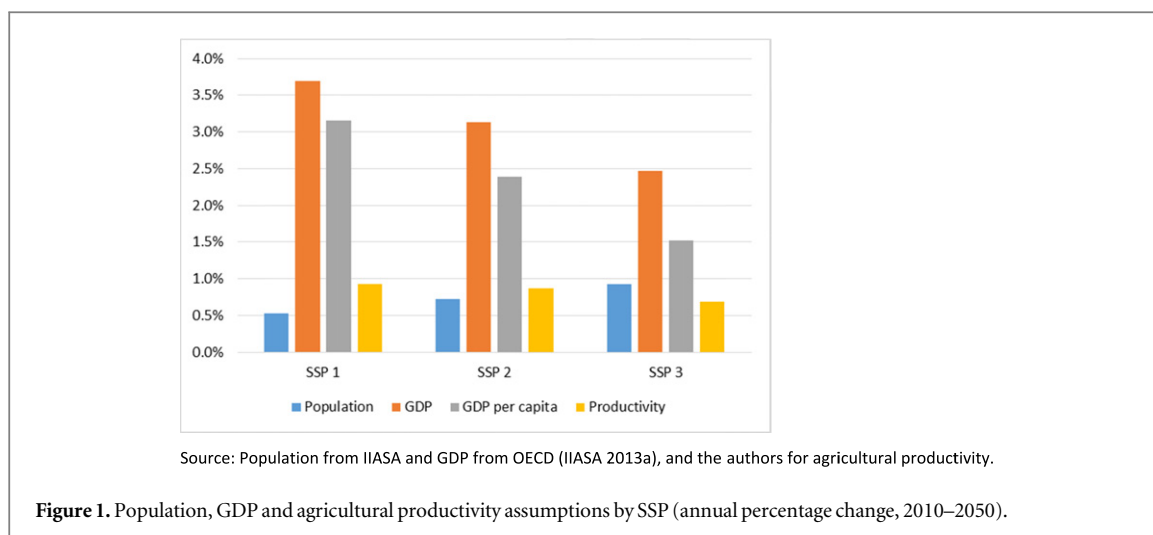
2. Methods

We begin by extending the range of SSPs considered. The full set of SSP storylines has been described in Krieger et al (2012) and O’Neill et al (2014, 2015). Within the SSP process, standardized input data on country-specific changes in population and income

have been developed (International Institute for Applied Systems Analysis (IIASA) 2013a)⁹. The SSPs are not intended to reflect specific policy or management choices, but rather different views about how the future may develop, given uncertainty about long-term changes in population, socioeconomic development, behavior and the role of global policy coordination. To date, the SSP framework has been mainly used to assess future scenarios relating to greenhouse gas emissions, mitigation options and policies, and changes in energy use and land use. In this paper, we use the SSP input data on population and income drivers to examine climate impacts on agricultural production and markets under three socioeconomic pathways (our specific implementation of SSP 1, SSP 2, and SSP 3). SSP 2 is a pathway with modest overall growth in population and incomes, and a slow pace of overall trade liberalization. SSP 1 features lower population growth, higher growth in per capita incomes, faster globalization and more integration of international markets, while SSP 3 describes a more fragmented world with less international trade, higher population growth, and lower growth in per capita incomes.

Building on these general scenario narratives, we add specific dimensions relevant to the agricultural sector, namely changes in agricultural productivity and agricultural trade policy regimes. Crop- and region-specific changes in agricultural productivity (‘intrinsic productivity growth rates’, or IPRs) had previously been taken from the IMPACT model’s ‘business as usual’ scenario for SSP 2 (Nelson et al 2014a, 2014b, von Lampe et al 2014). These IPRs summarize the improvements that can be achieved in agricultural productivity from a variety of advances in management practices, crop improvement and agricultural extension. For this paper, two additional sets of IPRs were developed for SSP 1 and SSP 3, using country-specific differences in economic growth between SSPs (relative to SSP 2) to adjust the IPRs upward or downward. Growth in income (as measured by gross domestic product, or GDP) was chosen as the primary driver to adjust the IPRs because public investment continues to be the primary driver of agricultural research and development, accounting for

⁹ The core quantification of the SSP drivers has involved a number of different research groups. The demographic projections were prepared at the International Institute for Applied Systems Analysis (IIASA), see KC and Lutz (2012). Three independent sets of GDP projections were developed—all harmonized to the IIASA demographic projections. The different GDP projections were prepared by IIASA, the Organization for Economic Co-operation and Development (OECD) and the Potsdam Institute for Climate Impact Research (PIK). All the SSP scenarios described herein refer to the OECD-based GDP projections, version 0.93. A fifth team based at the National Center for Atmospheric Research (NCAR) prepared projections of urbanization rates. All the data are available for public download at <https://secure.iiasa.ac.at/web-apps/ene/SspDb/dsd?Action=htmlpage&page=about>. IIASA (2013a) provides basic documentation of the main underlying features of the various projections.



almost 80 percent globally, and recent trends in public investment in agricultural R&D have followed GDP growth, especially in developing countries (Beintema *et al* 2012). Accordingly, agricultural productivity grows fastest in SSP 1 and slowest in SSP 3. (See supplementary material for more details on IPR adjustments, available at stacks.iop.org/ERL/10/085010/mmedia.) Assumptions for each of the three SSPs as implemented in this analysis (and harmonized across the global economic models) are summarized in figure 1.

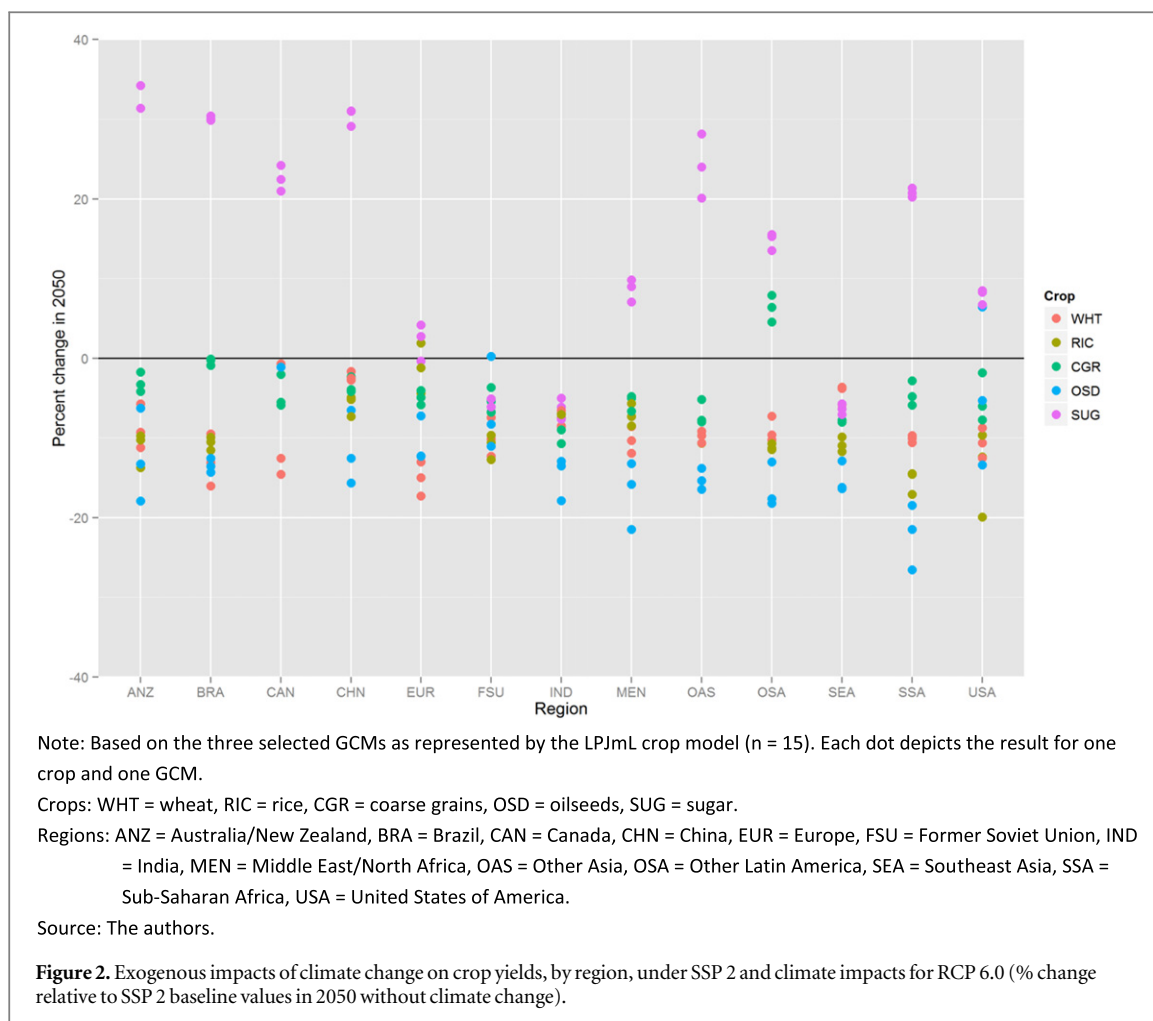
In principle, each SSP is consistent with multiple greenhouse gas emission pathways, depending on specific levels of emission mitigation efforts. For simplicity and in order to limit the number of scenarios, we combine each SSP with climate impacts for a unique RCP (Moss *et al* 2010, van Vuuren *et al* 2011, Krieger *et al* 2012): SSP 1 with climate impacts for RCP 4.5, SSP 2 with RCP 6.0, and SSP 3 with RCP 8.5. While this approach may entail some inconsistencies (e.g., we do not include the effect of greenhouse gas mitigation policies on land use), our scenario selection assures an analysis of the range of plausible climate outcomes by the middle of the century. To illustrate the effects of the different socioeconomic and climate impact pathways in isolation, additional SSP \times RCP combinations were analyzed using one global economic model (FARM, see below).

For each RCP, we use climate input data from three GCMs, namely HadGEM2-ES, IPSL-CM5A-LR, and MIROC-ESM-CHEM (Jones *et al* 2011, Watanabe *et al* 2011, Dufresne *et al* 2013), in order to account for differences in spatial distribution of projected climate change patterns, especially rainfall patterns, which are particularly important for agriculture (Intergovernmental Panel on Climate Change (IPCC) 2013). These models represent three of the five ISI-MIP GCMs that were selected by first availability (Hempel *et al* 2013). Of the ISI-MIP forcing data set (five GCMs), these three represent the ones with the strongest temperature

response and cover the full range of precipitation changes, where HadGEM2-ES is the driest and IPSL-CM5A-LR the wettest (Warszawski *et al* 2014)¹⁰.

These climate data are used as inputs in a global gridded crop model, LPJmL (Bondeau *et al* 2007, Müller and Robertson 2014), to generate quantitative estimates of the additional ‘exogenous’ impacts of climate change on crop yields for coarse grains, rice, wheat, oilseeds and sugar crops, i.e. before accounting for adjustments in area, prices or other variables. These exogenous climate impacts are represented as multiplicative shocks, and are derived using a delta approach as in previous AgMIP work (Müller and Robertson 2014, Nelson *et al* 2014a) to estimate relative yield changes per crop and region, allowing for more consistent application of climate change across models with different base yields and trends (Robinson *et al* 2014). Figure 2 shows these exogenous yield impacts, i.e. the difference between IPRs with and without climate change, for the five commodities under SSP 2 and climate impacts from RCP 6.0. (Similar results are found for the other RCPs; see figure S1 in the supplementary material.) The three dots for each commodity and region represent results from the three GCMs, and are in general relatively closely clustered. Exogenous yields for four of the five commodities are adversely affected by climate change, with the strongest impacts in most regions being on oilseeds. By contrast, climate change increases sugar yields in most regions, because for sugarcane the whole plant (including the stalk) is utilized, and total plant biomass of C_4 plants is only negatively affected at daily mean temperatures above 35 °C (see Müller and Robertson 2014 for more details). The performance of LPJmL has been compared to other global

¹⁰ In the 2050 timeframe analyzed here, global mean temperature change is not very different between GCM results for RCP 4.5 and RCP 6.0, and RCP 4.5 scenarios show slightly stronger warming and higher atmospheric CO₂ concentrations in 2050 than RCP 6.0 scenarios (Warszawski *et al* 2014).



crop models in previous studies and typically projects moderate changes compared to the AgMIP/ISI-MIP ensemble (see Rosenzweig *et al* 2014, figure 4) if CO₂ fertilization effects are excluded, as we do here (Müller and Robertson 2014, Rosenzweig *et al* 2014). In line with previous work, we do not consider fertilization effects on yields with higher CO₂ concentrations. The CO₂ effect is still very uncertain owing to many complex interaction mechanisms, and is widely discussed in the research community (Long *et al* 2006, Tubiello *et al* 2007, Wang *et al* 2012, Boote *et al* 2013).

Another key element in the SSP narratives is the pace of globalization and openness to international trade. Since this is an important aspect of agricultural markets and is potentially relevant for food security questions (Smith 1998, Schmidhuber and Tubiello 2007, Burnett and Murphy 2014), we consider two additional synthetic scenario variants on trade policy changes. In principle, changes in trade policy should already be part of each underlying SSP storyline, i.e. part of each SSP baseline run without climate impacts. However, in this study we separate agricultural trade policy changes from our specific SSP baselines in order to disentangle the specific effects on economic

model outputs. Hence the specific SSP 1, SSP 2 and SSP 3 baselines in this paper differ only with respect to changes in population, income and agricultural productivity (IPRs). Climate impacts in 2050 are then analyzed relative to the specific SSP baseline. To examine the impact of explicit changes in agricultural trade policy, we run two additional scenarios: SSP 1 with a liberalized trade variant and SSP 3 with a more restricted trade variant. The actual size of the trade ‘shocks’ reflects a specific interpretation of the SSP storylines as described in O’Neill *et al* (2015), but other plausible interpretations could be envisioned to assess the sensitivity of simulation outcomes relative to the trade shocks¹¹. In addition, one could envision as well a change in trade preferences, for example

¹¹ SSP 1 is a more globalized world, so in the liberalized-trade variant of SSP 1 we remove tariffs and export subsidies on all trade in agricultural and food products. The trade measures are phased out over the period 2020–2035. Domestic support policies are not affected. For the restricted-trade variant of SSP 3 the world is divided into three trade blocks: East and South Asia; a broad European block that encompasses Western and Eastern Europe, Central Asia, the Middle East and Africa; and a Western Hemisphere block that includes North, Central and South America. Import tariffs between the blocks are doubled (with no change to export measures), but no changes are imposed on trade policies within blocks. (More details are provided in the supplementary material.)

Table 1. Scenario definition.

Scenario	SSP	Radiative forcing	GCM	Trade policy	Economic model
1.0	SSP 1	No change	None	No change	ENVISAGE, FARM, IMPACT, MAGNET, MAGPIE
1.1		RCP 4.5	HadGEM		
1.2			IPSL		
1.3			MIROC		
1.4		HadGEM	Liberalized		
2.0	SSP 2	No change	None	No change	ENVISAGE, FARM, IMPACT, MAGNET, MAGPIE
2.1		RCP 6.0	HadGEM		
2.2			IPSL		
2.3			MIROC		
3.0	SSP 3	No change	none	No change	ENVISAGE, FARM, IMPACT, MAGNET, MAGPIE
3.1		RCP 8.5	HadGEM		
3.2			IPSL		
3.3			MIROC		
3.4		HadGEM	Restricted	ENVISAGE, FARM, MAGNET, MAGPIE	

Source: The authors.

a ‘buy local’ shift in preferences, that could be combined with (and possibly counteract) a reduction in trade barriers, but this is beyond the scope of this paper, which is to provide an illustrative example.

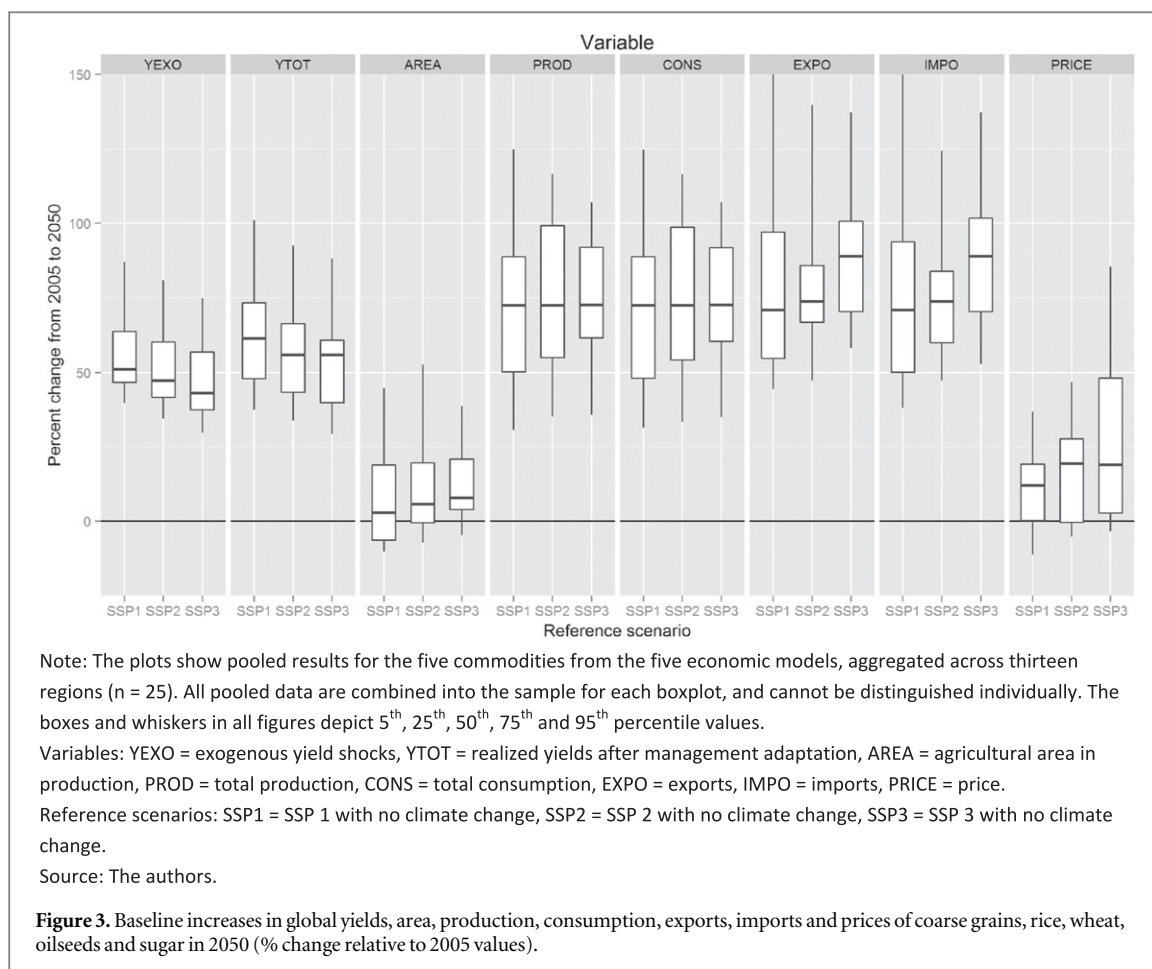
Five global economic models with a focus on agriculture are then used to analyze climate impacts in combination with the three SSPs and their associated changes in IPRs. Three are computable general equilibrium (CGE) models (ENVISAGE, FARM, and MAGNET), which examine economy-wide effects, and two are partial equilibrium (PE) models (IMPACT and MAGPIE), which include greater detail on the agriculture sector (Meijl *et al* 2006, Lotze-Campen *et al* 2008, Popp *et al* 2010, Rosegrant and the IMPACT Development Team 2012, Schmitz *et al* 2012, van der Mensbrugge 2013, Sands *et al* 2014, Woltjer *et al* 2014; see also supplementary material). This model selection allows us to cover a range of different implementations of food demand, land use, trade, and productivity increase, which are all important factors for determining market changes based on climate impacts on crop yields. The performance of these models has been assessed and compared in previous studies (Nelson *et al* 2014a, 2014b, Schmitz *et al* 2014, Valin *et al* 2014, von Lampe *et al* 2014). These results have also been used in the latest IPCC 5th assessment report (Intergovernmental Panel on Climate Change (IPCC) 2014). The economic models are used to generate three different baseline projections of agricultural yields, area, production, prices and trade for

coarse grains, rice, wheat, oilseeds and sugar to 2050 in the absence of climate change. These three baselines are then used as reference scenarios against which to compare the impacts of changes in climate as well as trade policy (table 1). As the socioeconomic drivers, climate patterns and trade policies are very different between the scenarios, we expect significant differences in results.

3. Results

3.1. SSP baselines to 2050

We are interested in the impacts of climate change and trade policy in 2050, so we need to first account for the changes in yield and other variables that will take place between now and 2050 due to other factors such as changes in population, income and technology, as described above (see figure 1) and in the supplementary material. Growth in these factors will be the major drivers of long-term changes in food demand, prices and supply over this time period, especially in the developing countries. Comparison of baseline scenarios 1.0, 2.0 and 3.0 (harmonized across the economic models on country-specific growth rates in population and income, and on crop- and country-specific growth rates in productivity, combined with current climate conditions), allows us to consider the effects of these drivers in the absence of climate change to 2050. All five economic models use the same GDP and population projections as exogenous model inputs. With the exception of MAGPIE, IPRs are implemented in



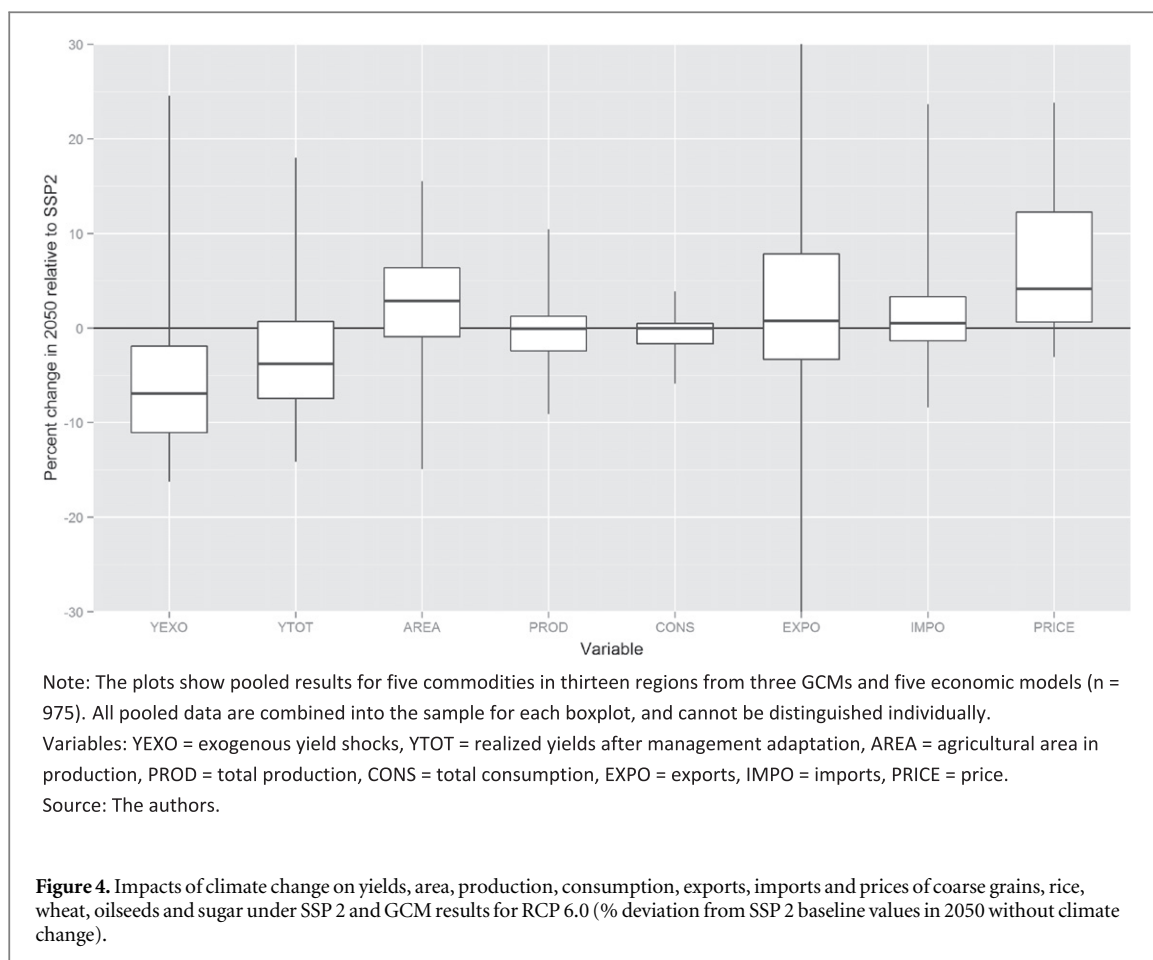
similar ways in the economic models. In the CGE models (FARM, MAGNET, ENVISAGE), the IPRs are implemented as land-augmenting shocks to production functions, while in the PE model IMPACT they are implemented directly as land productivity shocks. In the MAgPIE model, technology-based yield changes are determined endogenously, so here only the final yields are comparable to the other models (see also Nelson *et al* 2014a and 2014b, Robinson *et al* 2014 and supplementary material for details on IPRs for different SSPs).

As expected, baseline results vary across the three SSPs as we implement them in this paper (figure 3; see also the last row in figure 5). Consistent with higher economic growth driven by higher technological change and inelastic demand for agricultural products, SSP 1 shows larger yield increases and smaller price increases than the other two SSPs. The opposite is true for SSP 3, where yields increase less and prices increase more than in the SSP 1 scenario. Final yields (YTOT) are higher than exogenous yields (YEXO) as endogenous management decisions lead to intensification in times of economic growth (Meijl *et al* 2006, Eickhout *et al* 2009). Land is a relatively scarce production factor and land prices increase at a higher rate than labor and capital prices (it is a fixed factor and substitution is limited due to low land-price

elasticities), which induces land substitution by using more labor and capital. The use of more labor and capital per unit of land leads to an additional endogenous yield increase (intensification).

In the absence of climate change, global production and consumption of coarse grains, rice, wheat, oilseeds and sugar are projected to increase by an average (median) of 72–73 percent over 2005 levels by 2050¹². In contrast to the other variables, growth in production and consumption is essentially the same across the three reference scenarios, suggesting that the effects of differences in population and income growth offset one another across the three SSPs, and that inelastic demand for food and other agricultural commodities forces adjustments primarily in yields

¹² This is broadly consistent with the AgMIP phase 1 results, where total demand for food crops increased between 55 and 97 percent depending on the model (see Valin *et al* 2014). It is slightly higher than the 60-percent increase reported in the most recent FAO projection (see Alexandratos and Bruinsma 2012). It should be noted that the results reported herein reflect version 0.93 of the SSP quantifications, not version 0.5 as in Phase 1, and also reflect individual model changes, for example to consumer behavior, including income and price elasticities (see supplementary material). Furthermore, the Alexandratos and Bruinsma (2012) projections are based on a dated World Bank scenario for GDP that projected lower income growth than even the relatively low-growth SSP 3 scenario included in the present analysis.



and prices, and to a lesser extent in area¹³. Finally, although we do not model explicit differences in trade policy in these three scenarios, we see that trade increases significantly across the three SSPs. A number of factors will influence trade patterns, even while global production and consumption levels remain largely invariant to the SSPs. For example, population increase in developing countries under SSP 3 combined with population decrease in developed countries would induce agricultural surpluses in the latter and deficits in the former, all else equal. Land-use changes—both expansion of crop land and re-allocation of cropping patterns—differ across regions and will drive differential supply response to climate-induced changes in yields. Land-scarce countries with a low land supply response will lose relative competitiveness and increase net imports as increased demand leads to higher land prices (and therefore agricultural prices) instead of using more area, with a lower land price increase in the case of land abundant countries (see Meijl 2006, Eickhout *et al* 2009).

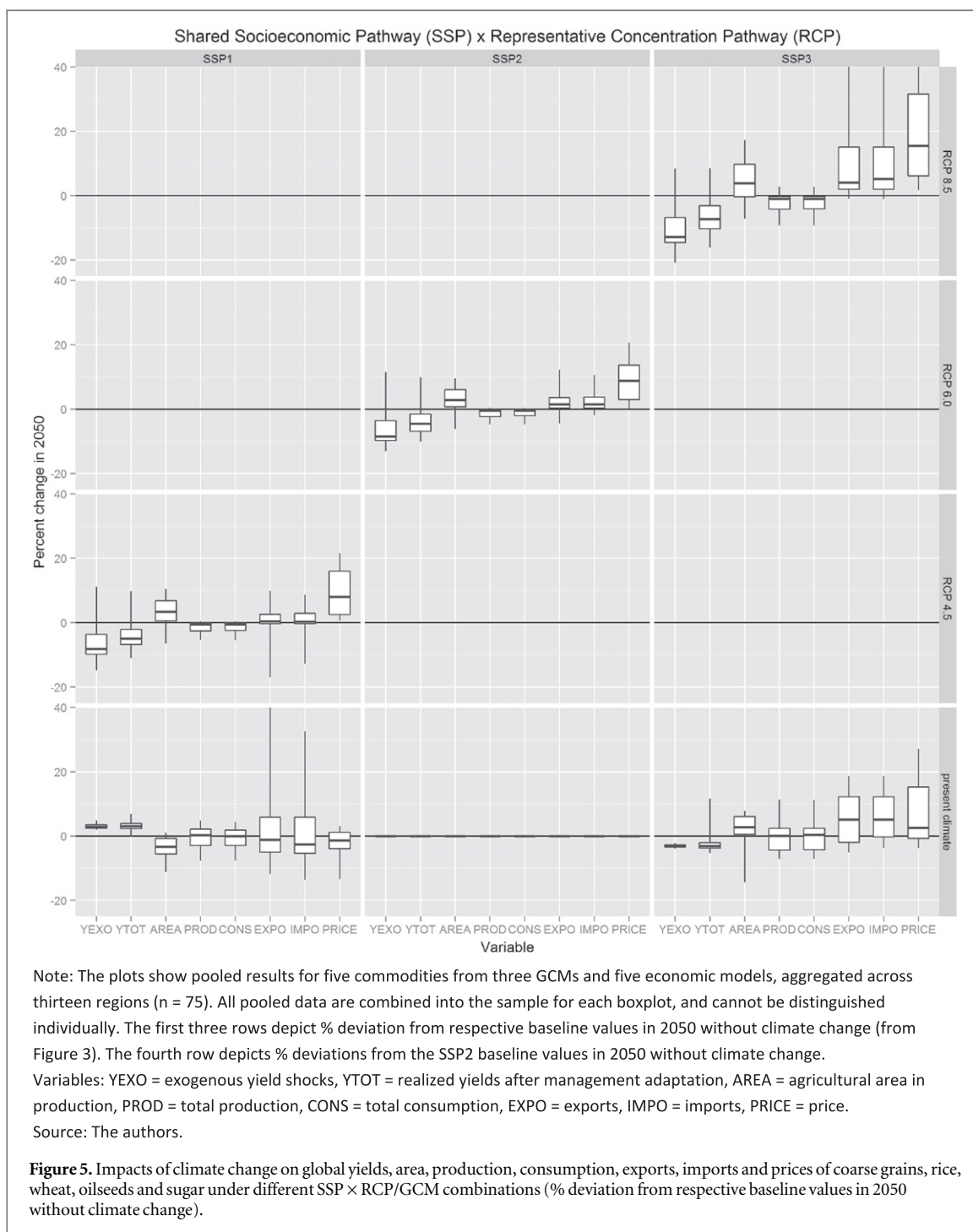
¹³ We do not assume differences in consumer preferences across SSPs here, although this is part of the SSP narratives (Kriegler *et al* 2012). One could imagine for example that the SSP 1 world might be one with less meat consumption as consumers' preferences towards more sustainable patterns of consumption lead to a decline in meat consumption in large parts of the world.

The variation evident in figure 3 reflects differences in results across the five crops and the five economic models. Further disaggregation (see supplementary material, figure S2) reveals a number of differences in baseline results across the economic models, highlighting the importance of including multiple models in the analysis.

These three baseline projections (scenarios 1.0, 2.0 and 3.0) give us a picture of what could be expected in 2050 without changes in climate or trade policy. All of the subsequent results in this paper are presented as deviations from these baselines.

3.2. Impacts of climate change

These baseline results are affected to different degrees by changes in climate. We look first at the central case of SSP 2 combined with climate impacts for RCP 6.0 radiative forcing (figure 4). In this scenario, climate change is initially projected to reduce 'exogenous' yields by an average of 6.9 percent (median across crops, regions and models relative to the baseline value in 2050)—before adjustments in area, prices and other variables are considered. The initial exogenous yield shocks trigger endogenous increases in area and prices. Higher prices in turn lead to increases in other production factors applied to these crops—and thus endogenous yield growth—as well as lower demand for agricultural commodities, reducing the final



impact of climate change on yields to a median decline of 3.8 percent. Area under the five crops increases by 2.9 percent, while production declines by 0.1 percent and prices increase by 4.2 percent. Median consumption is unchanged, but the variation around median consumption is much smaller than for the other variables. As we saw in the baseline scenarios (figure 3), inelastic demand for food and other agricultural commodities forces adjustments to exogenous shocks primarily through changes in yields, prices and area, while total production and consumption do not change significantly.

Similar patterns are evident for other SSP x RCP/GCM combinations. Figure 5 shows global climate impacts under SSP 1 and 3, each with climate impacts for a unique RCP. In the more ‘sustainable’ world of SSP 1, climate change driven by RCP 4.5 has impacts that are similar but slightly smaller than those under SSP 2 with climate impacts for RCP 6.0. The differences are small because GCM results for RCP 4.5 and RCP 6.0 are similar up to 2050 (with median YEXO declines of 8.2 percent and 8.5 percent for RCP 4.5 and RCP 6.0, respectively), and differences in population and income growth between SSP 1 and SSP 2 work to

offset each other in terms of their impact on food demand (see also figure 1). In SSP 3, by contrast, climate change driven by RCP 8.5 is projected to have greater impacts, with a median YEXO decline of 12.8 percent. Final adapted yields (YTOT) are projected to decline by a median of 7.2 percent, while area increases by 3.8 percent, production and consumption decline by 0.9 percent, exports and imports increase by 4.0 and 5.3 percent, respectively, and prices increase on average by 15.5 percent. The price effects vary more widely across the different crops and models than was the case for the other two scenarios.

The bottom row in figure 5 compares the SSP 1 and SSP 3 baselines directly with that of SSP 2. The median price changes and also the variation in price changes across crops, regions and models are lower across the last row than for the climate impacts moving up the columns. This suggests that the direct climate impacts in 2050 are stronger than the differences between the underlying socioeconomic trends, at least at the global level.

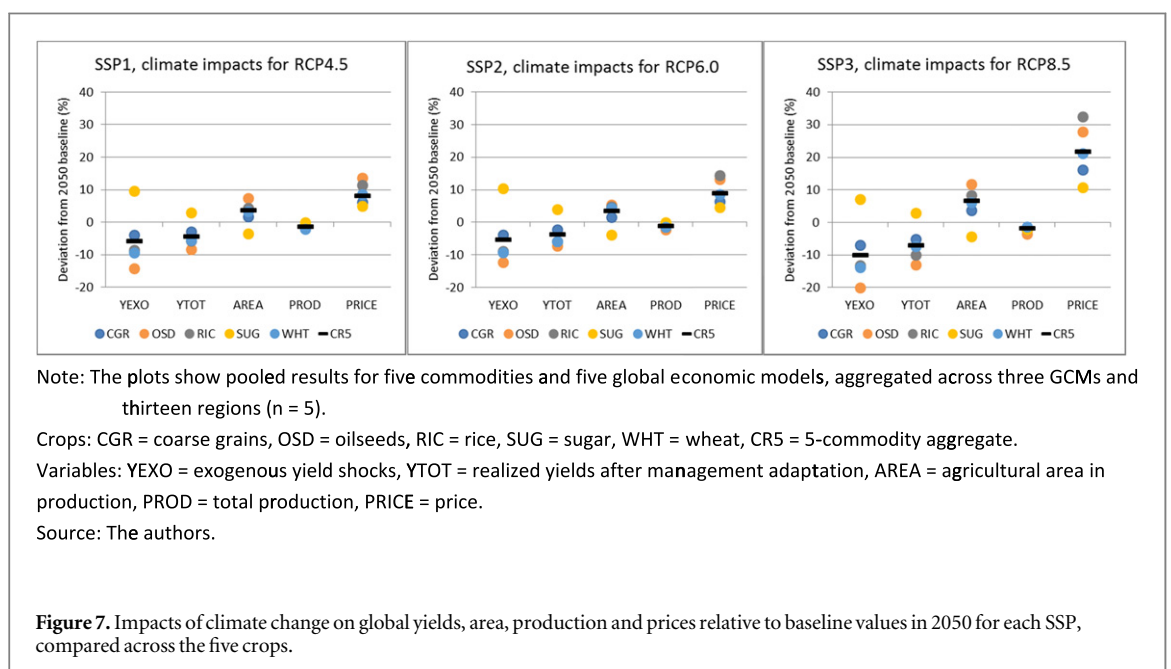
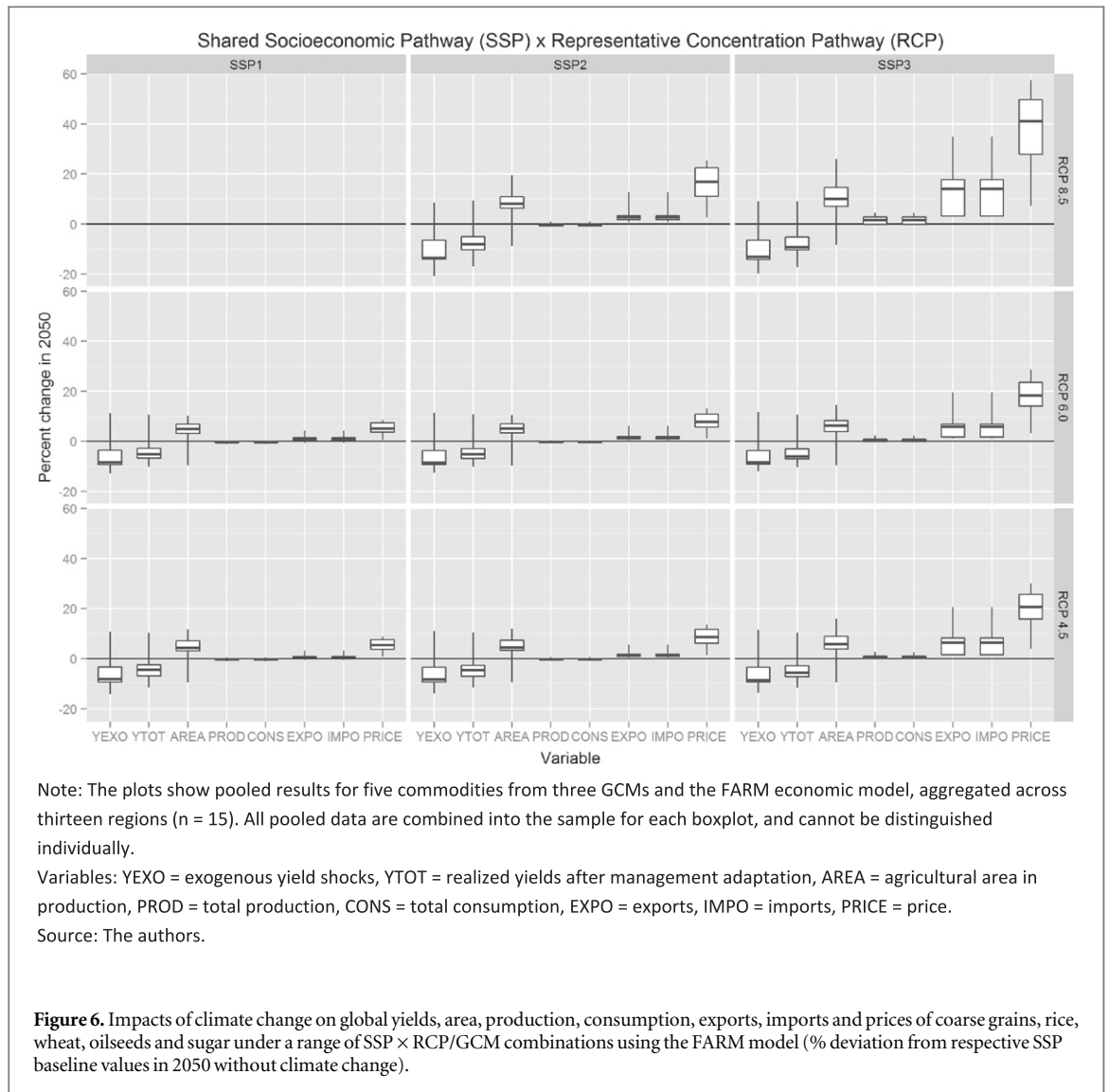
Aggregating across crops, regions and GCMs to isolate differences across the five economic models, we find that they generally agree on the direction of change in yields, area, production and prices in each scenario, although they differ in the magnitude of impacts, particularly in the scenario with the most rapid growth in population and emissions (SSP 3 with climate impacts for RCP 8.5). (See figure S3 in the supplementary material.) In all cases impacts on prices are larger than those on production because demand for food and other agricultural commodities is relatively inelastic. The variance across the economic models is also larger for prices than it is for the other variables, which is in line with results from previous studies, as the models differ substantially in their representation of demand and supply response, trade, and land supply (Nelson *et al* 2014a, 2014b, Schmitz *et al* 2014, Valin *et al* 2014).

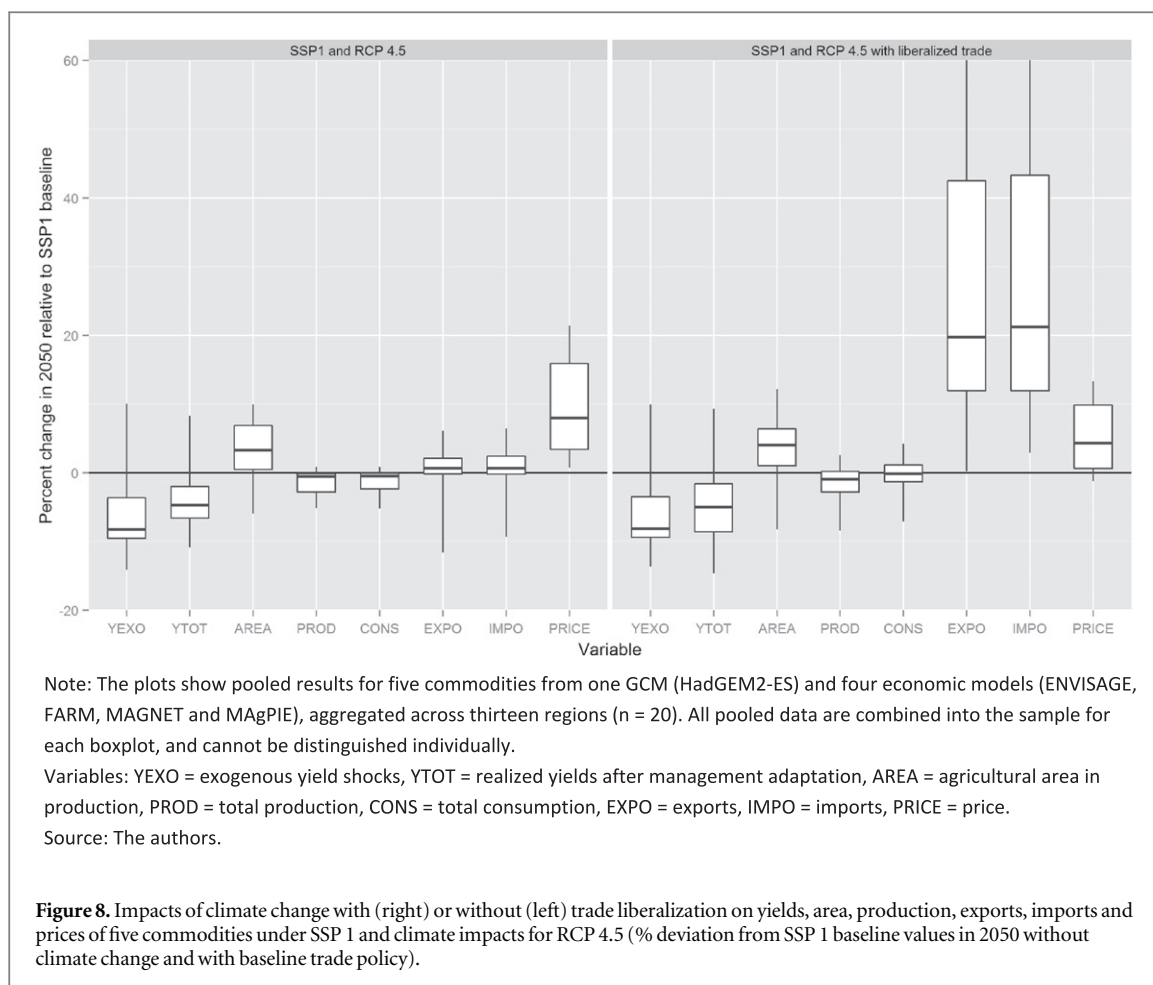
Because the matrix in figure 5 is incomplete, we are limited in our ability to distinguish the effects of differences across SSPs from the climate change differences across RCPs. In order to distinguish the effects of socioeconomic drivers from those of climate change, we ran a wider set of SSP \times RCP/GCM scenarios for one of the economic models, namely FARM. Results are presented in figure 6. It shows relatively small differences when moving along the rows, i.e. changing SSPs for a given RCP-related climate, especially between SSP 1 and SSP 2, but with a larger increase in impacts for SSP 3, most notably for exports, imports and prices. Moving up the columns, there is relatively little difference between climate impacts for RCP 4.5 and RCP 6.0 for a given SSP, consistent with expectations given the similarity between these concentration pathways until 2050. By contrast, climate impacts on all variables are greater under RCP 8.5 for both SSP 2 and SSP 3.

Compared to the projected changes in the baseline scenarios due to other drivers such as population, income and technology (figures 1 and 3), average climate impacts on yields projected by 2050 are relatively modest, although these conceal differences across crops and regions, which we will consider below. It is also important to note that this analysis does not capture the potentially significant impacts of inter- and intra-annual variability in temperature and precipitation, which is currently beyond the capabilities of most crop models, but also limited by available input data from climate models. For these particular scenarios, differences across the three GCMs are also relatively small—probably because the impacts of climate change are less significant (at least at the global scale) in the period leading up to 2050 than they are projected to be later in the century.

3.3. Differences by crop and region

In broad terms crop productivity often increases in areas with strong limitations by low temperatures (e.g. mountainous and high latitude areas) and decreases elsewhere, but there are multiple deviations from that broad pattern depending on local conditions. We find that adverse impacts of climate change appear to be particularly strong for oilseeds and rice, and more moderate for coarse grains and wheat across the scenarios examined (figure 7), which is also consistent with the AgMIP/ISI-MIP global gridded crop model ensemble analysis for RCP 8.5 (Rosenzweig *et al* 2014), where all individual models except for one (GAEZ-IMAGE) project larger yield declines for soy and rice than for maize and wheat, when assuming no CO₂ fertilization effects. Across regions, these patterns of crop-specific impacts also hold, but are subject to some variation, as for example soy is more strongly temperature limited in cooler regions and may see yield increases from climate change where wheat, which can deal with cooler temperatures, does not (Müller and Robertson 2014). Our results are similar to average historic impacts reported for recent decades for maize and wheat, and larger for oilseeds and rice (Lobell *et al* 2011, Intergovernmental Panel on Climate Change (IPCC) 2014), although comparison is difficult due to differences in methodology. Yield reductions are consistently greatest for oilseeds, while price increases are generally largest for rice, for which demand is more inelastic. By contrast, sugar crops are projected to have increased yields (as noted earlier), reduced area and comparatively modest price increases relative to the baseline (see also Müller and Robertson 2014 for a more detailed discussion). This contributes to mean yield impacts that are somewhat smaller than those in previous work that excluded sugar (Nelson *et al* 2014a). It also highlights the importance of further research on improved





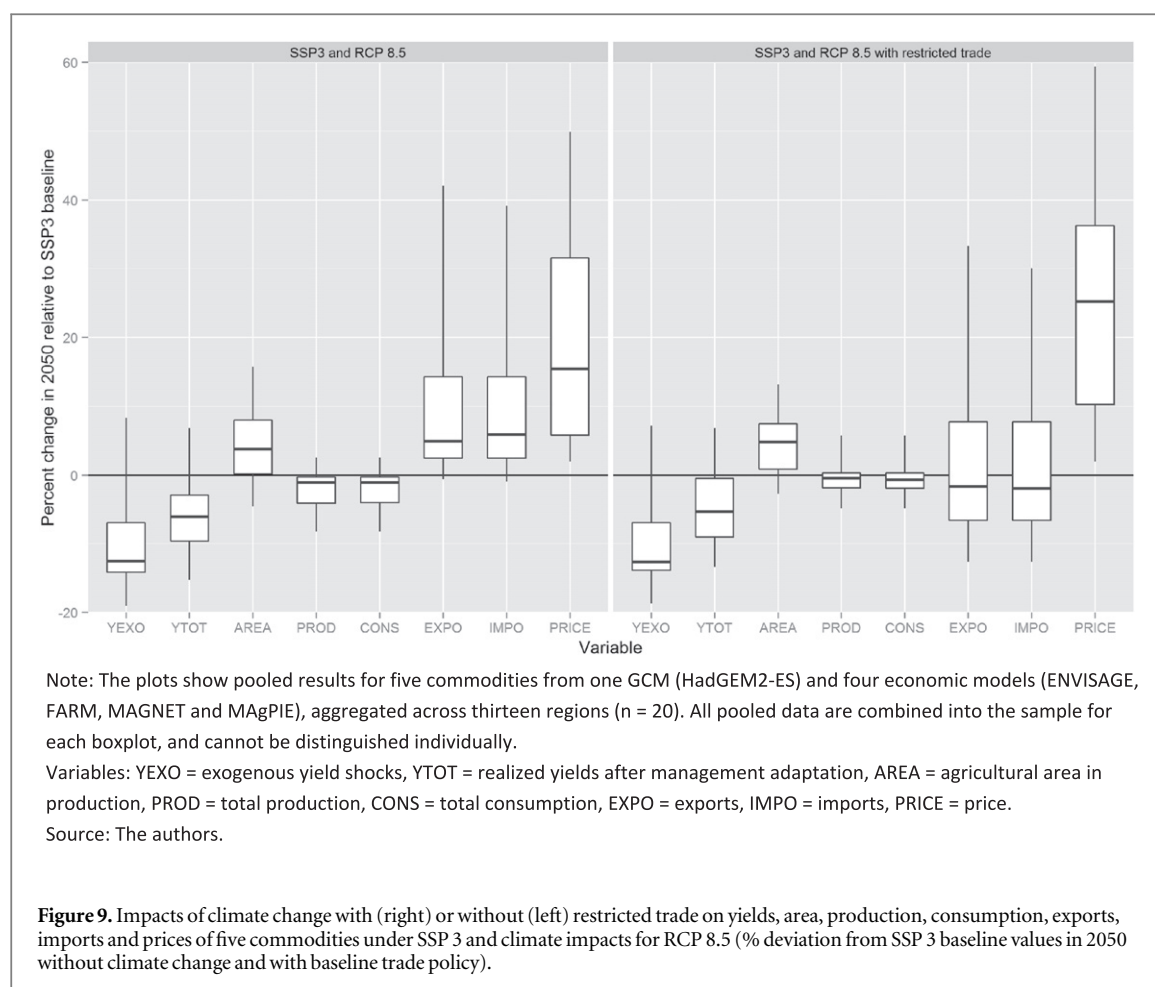
technologies to enhance adaptation, for example through increased tolerance of drought and heat.

Disaggregation by region shows that adverse yield impacts appear particularly strong for South Asia and Southeast Asia, and smaller in the other developing regions (see supplementary material, figure S4). Area increases are projected to be largest in sub-Saharan Africa and the Americas, consistent with other analyses (e.g. Alexandratos and Bruinsma 2012). Because of severe constraints on expansion of agricultural land, South Asia is projected to see larger price increases than the other regions under all three scenarios, with important implications for access to food.

3.4. Impacts of changes in trade policy

The results reported above assume no change in trade policies. Given the importance of trade to the global agricultural economy, we consider two additional scenario variants to explore sensitivity to trade policy assumptions: SSP 1 with more liberalized agricultural trade, and SSP 3 with more restricted trade, consistent with the underlying story lines of the respective SSPs. With more liberalized trade in SSP 1 we would expect smaller price increases on average compared to the no-change case reported earlier. This is confirmed in figure 8, the right panel of which shows

a sharp increase in trade and a lower price effect, an average increase of 4.3 percent, compared to 8.0 percent under 'business-as-usual' trade policies as reported in the left panel. By contrast, with more restricted trade in SSP 3 (figure 9), trade declines and prices rise on average by 25.2 percent, compared to 15.5 percent with 'business-as-usual' trade policies. The spread across crops and models is also wider. This shows the critical role that trade policy can play in helping to alleviate the adverse impacts of climate change and reducing price increases on international markets. Note that the figures reflect the price and trade impacts of different trade policies of the relevant scenarios with the climate shocks. It still holds that the climate shocks lead to price increases that could be partially or fully offset or exacerbated by changes in trade policies. A more elaborate study of trade policy effects would require additional baseline scenarios with, for example, more restricted trade in SSP 3 without climate impacts. However, this is beyond the scope of this paper, and admittedly limits our ability to isolate trade effects from climate impacts at this point. Moreover, we note that the economic models have very different trade mechanisms and trade policy implementations, and further work is needed to improve harmonization in this area.



4. Discussion

We find that projected reductions in agricultural yields due to climate change by 2050 are larger for some crops than those estimated for the past half century (Intergovernmental Panel on Climate Change (IPCC) 2014), but smaller than projected increases to 2050 due to rising demand and intrinsic productivity growth (table 1). Estimated impacts follow a similar pattern but are somewhat smaller than those of earlier work focusing on SSP 2 and climate impacts for RCP 8.5 (Nelson *et al* 2014a), which projected an 11 percent decrease in yields and a 20 percent increase in prices for a similar set of crops. Impacts are smaller for SSP 1 and SSP 2 than they are for SSP 3, and smaller for climate impacts associated with RCP 4.5 and RCP 6.0 than they are for RCP 8.5. The differences may arise for several reasons. First, in the previous work a second crop model (DSSAT) with more pronounced yield effects was used in addition to LPJmL, and a total of 10 economic models were applied in the analysis. LPJmL projections are representative for the middle of the crop model ensemble projections as analyzed for RCP 8.5 (Rosenzweig *et al* 2014) when CO_2 fertilization effects are excluded, as in the present analysis. Second, we apply climate impacts for different RCPs. Climate-induced yield changes for RCP 4.5 and RCP 6.0 by

2050 are relatively similar, but they are considerably smaller than for RCP 8.5 (see figures 5 and 6). Third, the economic models used in the present study have been further developed since the previous work, which led to changes (including greater flexibility) in their price responses (see supplementary material for details on specific models). Fourth, we use version 0.93 of the SSP drivers, which includes notable differences in population and income relative to version 0.5 that was used in the previous work (International Institute for Applied Systems Analysis (IIASA) 2013a, 2013b). For example under SSP 2, average per capita income is some 6.4 percent lower in 2050 under the latest projections compared with the earlier ones, and there is substantially more variation at the country level. And finally, we include sugar in addition to the four crops analyzed in earlier work (e.g. Nelson *et al* 2014a). In contrast to the other crops, sugar yields are shown to increase on average as a result of climate change in the scenarios examined in this study.

Endogenous behavioral responses (e.g. in food demand, area and other production factors) are critical in differentiating final yield impacts from initial exogenous climate shocks. While the models generally agree on the direction of changes in yields, area, production and prices, differences across economic models in the magnitude of impacts are sometimes

significant, due to different handling of demand, endogenous substitution effects, land supply, and international trade. We also show that changes in model outputs vary strongly across specific crops and regions. This holds especially for a SSP 3 world with increasingly diverse socioeconomic conditions and in which trade adjustments play a much greater role.

All scenarios show the potential for significant increases in prices for food and agricultural commodities, raising important concerns about food security, particularly for poor households. Differences in climate impacts between SSP 1 and SSP 2 are generally small, because exogenous yield shocks do not differ significantly between the two pathways, and because differences in population and income growth between the two pathways work to offset each other in terms of their impact on food demand. SSP 3 with RCP 8.5-related climate change generates impacts on yields and prices that are approximately twice as large as those under SSP 1 and SSP 2, as well as a wider spread across models, particularly in terms of price impacts.

The smaller differences we found between SSP 1 and SSP 2 may be due on the supply side to limited differences in IPRs (as we implemented them) across the scenarios. This question deserves further research. On the demand side, the smaller differences across these SSPs is also related to the fact that we focus primarily on staple crops, which are less responsive to income growth than are higher value commodities such as fruits, vegetables, and animal products. The relatively small differences between climate impacts for the RCP 4.5 and RCP 6.0 scenarios are related to the fact that large differences between these concentration pathways become evident only after 2050.

When trade is restricted, limiting options for adjustment to climate and other shocks, price increases are even greater and more widely spread across models. While harmonization of trade policies across models (let alone across countries) is a challenge, the results show that assumptions about trade policy matter significantly for diagnosing the projected adaptations and impacts. Response to assumptions about trade policy seems particularly sensitive in the case of SSP 3, in which trade adjustment plays a greater role than for the other SSPs, and for RCP 8.5, for which climate impacts are greater than for the other RCPs. The increased spread in price responses with more restricted trade also indicates the sensitivity of results with respect to the specific implementation of trade restrictions in the models. This reinforces the value of model comparison and the importance of more work on harmonizing the assumptions and implementation of trade policy assumptions. Moreover, while increased trade may help to alleviate pressures from combined social economic and/or climate impacts on agricultural production and prices, it may also entail other impacts and externalities potentially linked to them—both positive, for example increases in productivity embedded in increased inputs or investment (Huang

et al 2011) and negative, for example increases greenhouse gas emissions due to deforestation (Schmitz *et al* 2014b). Some of these externalities are dealt with explicitly in the SSP storylines (see for example O'Neill *et al* 2015), but are beyond the scope of this paper. The current exercise involves only a partial implementation of the SSP storylines and limits the isolation of trade policy effects from climate impacts on agricultural markets. However, much more elaborate implementations of the SSP storylines are currently being developed and compared across integrated assessment models, including a focus on agriculture by the AgMIP modeling teams. These will highlight a broader set of themes and the interconnections across policies (for example the links between trade policies and environmental impacts such as greenhouse gas emissions and deforestation), and will allow a more comprehensive analysis of trade policy impacts in a multi-model setting.

It is important to note a number of other caveats with regard to this study. First, in line with previous work, we do not consider CO₂ fertilization effects on yields with higher CO₂ concentrations. The CO₂ effect is still very uncertain in the crop models owing to many complex interaction mechanisms, and it is widely discussed in the community. Omitting CO₂ fertilization effects would tend to suggest that our results err on the pessimistic side.

On the other hand, other omitted effects would tend to suggest that our results err on the optimistic side. For example, current crop models (together with limited inputs from GCMs) are not able to capture some potentially negative effects of climate change, such as the effects of extreme temperatures and precipitation, changes in pests and diseases, and ozone levels (Lobell and Gourdji 2012). These are likely to be significant (see e.g. Heft-Neal and Roland-Holst 2015), but incorporation in long-term projections awaits future modeling improvements.

Third, assumptions on adaptation in this study are limited to endogenous responses within the economic models, but improvements are needed in both economic and crop models in this regard. This also reflects the existing lack of conceptual and applied approaches for explicit assessments of adaptation options in this kind of aggregate economic models. While the economic models have some flexibility in factor substitution (e.g. using more labor, capital or intermediate inputs to compensate for less productive land), they do not cover large-scale endogenous investments for climate change adaptation (e.g. building new dams for increasing irrigation water availability or protective measures against sea-level rise). Moreover, endogenous R&D investments in climate-adapted crop varieties are not covered by most economic models.

Fourth, a number of other important dimensions are not yet incorporated in the scenarios we analyzed. Based on the RCP and SSP work in climate change

mitigation assessments, it has been proposed to develop more detailed ‘representative agricultural pathways’ (RAPs) (e.g. Valdivia *et al* 2015). These need to be discussed and agreed upon in the wider agricultural modeling community (including biophysical as well as economic modelers), and should provide background information for a broad range of climate and global change impact studies at regional and global levels. In this study we take initial steps to better define scenario inputs with respect to agricultural productivity change and trade policy change for a subset of three SSPs. A comprehensive description and definition of global RAPs would require coverage of several key additional dimensions, potentially including agricultural land supply, environmental protection, and changes in dietary preferences, as well as a mapping of RAPs with all five SSPs and their particular storylines.

5. Conclusions

These findings illustrate the sensitivity of climate change impacts to differences in socioeconomic and emissions pathways, particularly for those characterized by slower economic growth (SSP 3) and higher emissions (RCP 8.5), and for which the impacts of climate change on yields, areas, prices and trade are relatively large. This in turn reinforces the importance of systematic comparison across more RCP/GCM × SSP combinations (including for SSP 4 and SSP 5, which were not included in the present study), as well as more detailed implementation of the various SSP storylines across several key dimensions.

Among those areas deserving further research are further development of RAPs, including dimensions such as agricultural land supply, changes in dietary preferences, and domestic farm policies as well as international trade (more systematically comparing baselines with climate impact scenarios); analysis of additional emissions pathways and SSP-specific mitigation strategies, especially bioenergy demand, biomass production and its effect on land use and crop prices; examination of regional results across models; and inclusion of additional climate, crop and economic models to further understand and potentially narrow differences in results. Topics deserving closer attention also include changes in inter- and intra-annual variability associated with climate change, improvement in our understanding of CO₂ fertilization effects as well as changes related to pests and diseases, and implications for food security at global, national and subnational scales. Work on many of these topics is currently under way through the Agricultural Model Intercomparison and Improvement Project (AgMIP) (Rosenzweig *et al* 2014).

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