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Avoided economic impacts of climate change on agriculture: Integrating a land surface model (CLM) with a global economic model (iPETS)

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ABSTRACT

Agricultural systems provide food and are also an important part of the economy for many countries, but crop yields are vulnerable to the effects of climate change. We assess the global impacts of climate change on agricultural systems under two climate projections (RCP8.5 and RCP4.5) in order to quantify the difference in impacts as climate change is reduced. We also employ two different socioeconomic pathways (SSP3 and SSP5) to assess the sensitivity of results to the underlying socioeconomic conditions. The integrated Population-Economy-Technology-Science (iPETS) model, a global integrated assessment model for projecting future energy use, land use and emissions, is used in conjunction with the Community Earth System Model (CESM), and particularly its land surface component, the Community Land Model (CLM), to evaluate climate change impacts on agriculture. iPETS results are produced at the level of nine world regions for the period 2005-2100. We employ climate impacts on crop yield derived from CLM, driven by CESM simulations of the two RCPs. These yield effects are applied within iPETS, imposed on baseline and mitigation scenarios for SSP3 and SSP5 that are consistent with the RCPs. We find that the reduced level of warming in RCP4.5 (relative to RCP8.5) can have either positive or negative effects on the economy since crop yield either increases or decreases with climate change depending on assumptions about CO2 fertilization. For example, yields are 10% lower, and crop prices +17% higher, in RCP4.5 relative to RCP8.5 if CO2 fertilization is included, whereas yields are 20% higher, and crop prices 19% lower, if it is not. We also find that in the mitigation scenarios, crop prices are substantially affected by mitigation actions as well as by climate impacts. For the scenarios we evaluated, the development pathway (SSP3 vs SSP5) has a larger impact on outcomes than climate (RCP4.5 vs RCP8.5), by a factor of 3 for crop prices, 11 for total cropland use, and 21 for GDP on global average.

Keywords: Avoided impacts, climate change, crop yields, CO2 fertilization, integrated assessment

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1 Introduction

Crop yields are vulnerable to the effects of climate change (Schlenker and Roberts, 2009). As a crucial part of many economic systems, a change in agricultural systems will affect the overall economy. Several recent studies have assessed global impacts on agriculture under combinations of assumptions about future climate outcomes and societal development. Most prominently, a major model comparison activity, the Agricultural Model Intercomparison and Improvement Project (AgMIP), is evaluating climate impacts on agricultural systems from various perspectives. In the first phase of its global economic analysis, AgMIP focused on a high climate change outcome associated with Representative Concentration Pathway (RCP) 8.5, the highest of the four RCPs (van Vuuren et al. 2011), combined with a central societal development pathway, the Middle of the Road Shared Socioeconomic Pathway (SSP2; O'Neill et al. 2014). They found that without CO_2 fertilization (the enhanced plant growth from higher atmospheric CO_2 concentration), climate generally has negative effects on crop yields, which vary widely across regions and crops. Global average yield change ranges from -4% to -20% in 2050 for the average of five main crops (wheat, rice, coarse grains, oil seeds, sugar) based on different climate and crop models (Nelson et al. 2014). The yield reductions resulted in a 3% to 79% increase in average crop prices and a -2% to +26% change in total cropland across models (von Lampe et al. 2014).

Other studies show that different climate and development pathways can have quite different impacts on agricultural systems. Wiebe et al. (2015) extends the AgMIP studies by incorporating multiple climate and socioeconomic scenarios to show that, again without CO_2 fertilization, climate impacts on crop yields are generally negative, a median of -12.8% for RCP8.5, and this increases crop prices by 15.5% on average across multiple models in 2050 compared to SSP3 no climate change scenarios. Impacts for RCP4.5 and 6.0 are similar with each other but smaller than for RCP8.5. However, societal conditions (SSPs) are varied along with the climate outcomes in this study, which limits the possibility to draw conclusions on which factors are driving results. Hasegawa et al. (2013) estimate impacts of climate change with CO_2 fertilization on agriculture under multiple scenarios (all 12 combinations of SSP1, 2, and 3 along with RCP2.6, 4.5, 6.0 and 8.5) focusing on calorie consumption and population at risk of hunger. They find that although climate change increases risk of hunger evaluated by per-capita calorie intake (RCP8.5 reduces per-capita calorie intake -2.1% for SSP3 in 2050), different socioeconomic pathways have greater impacts. For example, per-capita calorie intake is 14% higher in SSP1 than in SSP3 without considering climate change, and 10% higher in SSP2 compared to SSP3. However, they do not focus on the benefits of mitigation by comparing results at different levels of climate change within the same societal development pathway.

The Climate Change Impacts and Risk Analysis (CIRA) project by EPA evaluates impacts in the U.S. from two different scenarios: a reference scenario without action on climate change with total radiative forcing level of $10W/m^2$ and a mitigation scenario that limits global warming to 2°C above preindustrial level (radiative forcing level close to $3.7W/m^2$). They examine consequences for various sectors, including agriculture (EPA 2015). Their study on the agriculture sector indicates that, with CO_2 fertilization, mitigation to the lower forcing pathway increases yields for most crops in the USA, with up to 40% yield increases in 2100 for corn, soybean and wheat leading to a $32 to $50 billon ($2005) welfare gain from 2015 through 2100 (discounted at 3%; Beach et al. 2015).

In this study we assess the global impacts of climate change on agriculture under two different climate projections (RCP8.5 and RCP4.5) and two different socioeconomic pathways (SSP3 and SSP5) in order to quantify the difference in impacts on agricultural systems as climate change is reduced, and the dependence of this difference on the socioeconomic development pathway assumed. Also, while temperature increases in many regions might be harmful to crop growth, a higher CO2 concentration in the atmosphere might foster plant productivity (especially for C3 plants; e.g., Kimball 2010; Lobell and Gourdji 2012). The few previous studies that included CO_2 fertilization did not quantify the sensitivity of their results to this uncertainty (e.g., Hasegawa et al. 2013). Beach et al. (2015) analyzed the sensitivity of yields to CO_2 fertilization but did not assess the consequences for the agricultural sector or wider economy. We decompose the total climate effect on crop yield changes into a CO_2 fertilization effect and a climate effect (changes in temperature and precipitation) and perform economic impact analyses with CO2 fertilization and without.

This paper is part of a larger study on the Benefits of Reduced Anthropogenic Climate Change (BRACE, O'Neill and Gettelman, this issue) that examines differences in impacts between RCP8.5 and RCP4.5 for a range of different sectors and outcomes. We draw on BRACE simulations of climate impact on crop yields from Levis et al. (this issue); Tebaldi and Lobell (this issue) also project global crop yield impacts using an empirical approach. In section 2 we outline our methodology. Section 3 reports results, and section 4 summarizes conclusions and discusses caveats, and points to future research needs.

2 Methodology

We model the effect of climate and atmospheric CO_2 changes on global and regional economies through their effects on crop yields. We use the integrated Population-Economy-Technology-Science (iPETS) model, a global integrated assessment model for projecting future energy use, land use, and emissions, in conjunction with the Community Earth System Model (CESM), and particularly with the Community Land Model (CLM, Oleson et al. 2013). The analysis is global, with results in iPETS produced at the level of nine world regions and in CLM at a resolution of 2 degrees, and spans the period 2005-2100. We draw on CLM simulations reported in Levis et al. (this issue) for RCP8.5 and RCP4.5 to derive climate impacts on yield for our analysis (more on this below). These yield effects are applied within iPETS, imposed on four no-climate scenarios combining SSP3 and SSP5 with RCP8.5 and 4.5. These four scenarios were chosen to span a high and medium level of climate change (the latter assuming emission mitigation takes place), as well as low and high societal vulnerability to climate impacts (O'Neill and Gettelman, this issue). Future impacts in each scenario (relative to a no-climate scenario), as well as impacts avoided by following RCP4.5 rather than RCP8.5, are measured in terms of differences in yield, food prices, consumption, GDP and land use, with and without CO_2 fertilization.

Multiple models and tools are required to carry out the analysis and the overall workflow is shown in Fig.1. We provide a basic description of the process here; more detailed information on each component can be found in the Electronic Supplementary Material (ESM).

First, we use iPETS (for a description of model structure see ESM1) to develop SSP5 and SSP3 baseline (no mitigation) scenarios without climate change by calibrating the model to match existing scenarios produced with the Global Change Assessment Model (GCAM, Brenkert et al. 2013), a more comprehensive integrated assessment model with a long history of use in climate change analysis. The value of the iPETS analysis is in the estimation of the climate-driven changes to the economy, rather than the simulation of the no-climate scenarios themselves. The calibration reproduces GCAM outcomes for GDP, CO2 emissions, energy demand, land use and cropland yield, aggregated to iPETS regions, by modifying key iPETS model parameters such as labor productivity, total factor productivities of energy and crop production and partial factor productivities of energy and land (for details see ESM2). The calibration produced outcomes for targeted variables that deviated by less than 1% averaged over the period 2005-2100. The GCAM SSP5 baseline scenario produces about 8.5W/m^2 of forcing by 2100. Since iPETS's energy system and land use is tuned to match GCAM's, iPETS radiative forcing is assumed to match as well, and is therefore consistent with climate outcomes based on RCP8.5. However the GCAM SSP3 baseline scenario produces only about 7W/m2 of forcing by the end of the century. Since we are interested in the climate impacts under RCP8.5 for both SSPs in order to evaluate the sensitivity of impacts to societal conditions, we developed a high growth SSP3 baseline scenario (SSP3HG), with an increased GDP growth rate relative to the GCAM SSP3 scenario, such that the CO_2 emissions from energy consumption (and by extension, CO2 equivalent emissions) from a larger scale of the global economy are consistent with RCP8.5 (see ESM3 for details). We also developed no-climate mitigation scenarios, SSP5-4.5 and SSP3HG-4.5, by employing a carbon tax on energy to reduce emissions to the level of RCP4.5 (see ESM4 for details). The no-climate baseline scenarios (SSP5-8.5, SSP3HG-8.5) and no-climate mitigation scenarios (SSP5-4.5, SSP3HG-4.5) project cropland demand for all iPETS regions for the next century. A dynamic statistical downscaling model developed by Meiyappan et al. (2014) is used to spatially allocate cropland within each region for these scenarios, producing a global gridded crop map for each time period and scenario (see ESM5 for details).

Climate impacts on yield are obtained using CLM4.5. The version of CLM employed here represents eight crop types (temperate corn, soybean, spring wheat-rye-barley[1], sugarcane, rice, cotton, tropical corn, and tropical soybean) and allows for nitrogen fertilizer application and irrigation (Levis et al. this issue). However, CLM does not represent transient land use change; instead, the spatial distribution of cropland and pasture remains fixed over time, as do assumptions about the level of nitrogen fertilizer application and irrigation area. To accommodate these characteristics of the model, as well as to reduce overall computing time, we do not link iPETS directly to CLM but instead produce in advance a CLM yield database from a number of idealized simulations and use the results to estimate climate impacts on yield over time.

The yield database includes annual yield information for all CLM crop types at every grid cell under different climate scenarios and management assumptions (with and without fertilizer, irrigated and rainfed; Levis et al. this issue; see ESM6 for details). To obtain climate effects on yield for iPETS regions for a given scenario, we first use the crop maps from the downscaling model for each time step to select grid cells from the CLM yield database for the desired climate and CO_2 assumptions. Regional yield values are calculated by aggregating the spatial, crop-specific yield information into one average crop type for each iPETS region. This process is repeated for a constant climate (no climate change) scenario, and the difference between the two results gives the climate effect on regional yield. These yield changes are calculated by a crop yield tool which involves several additional steps beyond those described above, including yield adjustments for irrigation and nitrogen fertilizer assumptions and smoothing of CLM outputs (for details see ESM7).

The climate-driven yield differences are then applied in iPETS by modifying the total factor productivity of crop production by the same percentage change. Each of the four iPETS scenarios is run again, producing a new set of results, including GDP, energy demand, food demand and land use demand. The difference between this set of results (with climate effects) and results for the no-climate scenarios gives the climate impact on the economy. Because cropland demand in iPETS adjusts with new yields, additional iterations are needed to produce consistent results for the scenarios with climate effects. We iterate the process of using the new cropland demand (after spatially downscaling) to re-calculate the climate effect on yield from the CLM yield database and rerun iPETS with the new yield effects until the cropland demand for each region at each time step in iPETS converges.

3 Results

3.1 Regional Aggregated Yield Change

Climate-driven yield changes for the iPETS regions are plotted in Fig.2 for SSP5-8.5 and SSP5-4.5 with and without CO_2 fertilization. As described in the previous section and in more detail in ESM7, these yield outcomes are based on CLM results from idealized

[1] Rye and barley parameterized as spring wheat.

experiments, and then modified to be consistent with SSP-based assumptions about fertilizer application rates over time, and outcomes for changes in extent and spatial location of crops, for each iPETS region. The yield changes for SSP3HG are similar to SSP5 and are shown in ESM Fig.10. With CO_2 fertilization, the yield changes are generally positive in almost all regions after 2050 (yield changes >1) and RCP8.5 shows higher yield gains than RCP4.5, with global average yield increases of 18% and 12% for 2061-2080, respectively. However, if CO_2 fertilization is excluded, the climate impact on yields is negative in most regions and RCP 8.5 has higher global average yield losses (-10%) than RCP4.5 (-6%).

These results are broadly consistent with previous projections of climate and CO_2 effects on yield. For example, as part of the first phase of AgMIP, seven global gridded crop models projected global yield changes by the end of the century under RCP8.5 ranging from -35% to over +60% with CO_2 fertilization for maize, wheat, rice and soy, with the majority of the yield changes being positive, especially for wheat and rice (Rosenzweig et al. 2014). Without CO_2 fertilization, the same models produced yield changes of -60% to +15%, with almost all effects being negative. In comparison, the corresponding global average yield changes in RCP8.5 in our analysis are +26% with CO_2 fertilization and -18% without it in 2100.

Fig.3 summarizes the separate effects of climate (temperature and precipitation) and CO_2 fertilization on yield changes in 2061-2080 for the SSP5-8.5 scenario. The total yield effect (climate and CO2) is the difference between yield in the SSP5-8.5 scenario with both climate and CO_2 change and in the same scenario with both climate and CO_2 held constant (i.e., the yield effects shown in Fig.2a). This total effect is partitioned into separate climate and CO_2 effects using yield changes in a scenario with climate change but constant CO_2 levels. The CO_2 fertilization effect is then further partitioned into a direct CO_2 effect and an interaction effect between higher CO_2 levels and increasing fertilizer application rates (CO_2 fertilization effect is stronger when nitrogen fertilizer rates are higher; Kimball, 2010). This further decomposition is achieved using yield changes in a scenario with climate change, constant CO_2 and constant nitrogen fertilizer application rates.

All three effects are substantial and CO_2 fertilization has a larger effect than climate in all regions. The overall average yield gains in 2061-2080 for all regions range from 5% to 31%. CO_2 fertilization contributes 15% to 45% (>20% for most regions), while the climate effects from temperature and precipitation changes decrease yields by 8% to 21%. The CO_2 fertilization effect is mostly due to the direct benefit of CO_2 on crop growth, but the interaction effect with increasing nitrogen fertilizer application rates also contribute to yield increases from 1% to 13% (<5% in most regions).

The relative magnitudes of these effects vary across regions. Regional differences in CO_2 fertilization effects are driven partly by differences in crop composition, since C3 crops, such as rice, wheat, soybean, and cotton, benefit most from CO2 fertilization. With a 95% share of C3 crops, Other Industrialized Countries has the highest CO_2 fertilization effects. Variations are also affected by differences in climate (temperature and precipitation), absolute levels of nitrogen fertilizer, and water availability (McGrath and Lobell 2013). All regions show negative effects from climate change except for China, where yield declines for most crop types in most regions are offset by yield increases for cotton and maize in the northeast and rice in the southeast. Interaction effects between CO2 fertilization and nitrogen fertilizer effects are generally large in regions where fertilizer rates increase fast and CO2 fertilization effects are high, such as India, Other Developing Countries and Transition Countries. The interaction effects are small for China, the EU, USA and Other Industrialized Countries due to very small fertilizer application rates change (rates for China, EU and USA are kept current CLM levels, see ESM7). Small interaction effects for Latin America and Sub-Saharan African result from their small direct CO_2 fertilization effect (due to the crop mix).

3.2 Climate Impact on Individual Scenarios

The economic impacts of climate change for individual scenarios are calculated by comparing the iPETS model outputs with climate and CO_2 effects to the outputs without those effects. We also illustrate the effect of uncertainty in CO_2 fertilization by assessing impacts with climate change but without CO2 fertilization. Fig.4 shows both types of results for SSP5-8.5 in 2061-2080. Impacts in other scenarios are qualitatively similar and are shown in ESM Fig.11 and 12.

Generally, crop yields increase in all regions from climate (with CO_2 fertilization) effects in SSP5-8.5 leads to increases in crop production and consumption and decreases in crop prices. There is an overall benefit to GDP up to 3%, and the cropland used in production increases (while pasture area declines). The principal explanations for these responses are that, when there is a yield increase, ceteris paribus, crop production costs fall and therefore the crop industry will generally increase production. The larger supply reduces the crop price and thus consumer crop consumption increases. In this scenario crop prices decrease 8% to 28% (in response to yield increases of 2% to 26%).

The effect of the yield increase on cropland use is more complicated. Increased production does not necessarily imply increased land use, since yield per hectare of cropland is higher. The net result depends on many factors including how large the yield increase is, how easily the producer can shift inputs toward land use, input prices, the demand response to lower crop prices, etc. Our model outputs show that in this scenario, the balance of these effects leads to a cropland increase, yet percentage increases in cropland are smaller than increases in crop production.

Decreased crop prices also decrease the price of animal products, for which crops are a major input. The reduction of both food sector prices leads to an increase in total food consumption, although the effect is not large given that food consumption is relatively inelastic (i.e., it doesn't change much in response to price changes). Food consumption shifts away from animal products toward crops, because the price reduction is smaller for animal products than for crops. This shift results in a reduction in demand for animal products and consequently a decrease in demand for pasture land.

The yield changes include effects from CO_2 fertilization (including the interaction effect with fertilizer shown in Fig.3). As shown in Fig.4, if CO_2 fertilization effects are excluded, yields in almost all regions decreases up to 24% and the economic impacts are reversed: crop prices increase up to 45% and GDP declines up to 2%.

3.3 Avoided Impacts from Climate Change

Estimating the avoided impacts if we mitigate climate change from RCP8.5 to RCP4.5 requires disentangling two different effects on the economy: those due to the impacts of climate change on crop yields, and those due to the carbon taxes imposed to reduce emissions to meet the RCP4.5 forcing target. The combined effects are given by the difference in outcomes between SSP5-8.5 and SSP5-4.5 (and similarly for SSP3HG). To decompose this difference into separate impact and mitigation effects, we carry out additional iPETS runs that include only one effect: SSP5-4.5 and SSP3HG-4.5 with emissions mitigation occurring to reduce forcing to the RCP4.5 pathway, but with yield effects remaining at their level according to RCP8.5. The results for SSP5 are shown in Fig.5 both with and without CO_2 fertilization (results for SSP3HG are shown in ESM Fig.13).

When CO2 fertilization is included, RCP4.5 leads to yield losses of <10% in all regions relative to outcomes in RCP8.5. The lower yield alone induces decreased crop production and consumption, higher crop prices (<15%), less cropland demand, and reductions in GDP (<0.7%). The mitigation effects are more complex. When a global carbon tax is applied to all regions to achieve the RCP4.5 emissions level, the effect differs across regions due to differences in economic structure and energy systems. Resulting changes in relative prices across different energy goods mainly affect production, consumption and trade of those goods, as well as the overall economy. Generally speaking, mitigation actions increases the price of carbon intensive energy use, thus reduces consumption (especially energy consumption), and GDP.

If CO2 fertilization is excluded from the analysis, mitigation (RCP4.5) induces positive yield changes (relative to RCP8.5) in most regions and thus results in increased crop production and consumption, higher cropland demand, lower crop prices, and increases in GDP relative to RCP8.5. The yield gains from mitigation are <10% for most regions with Transition Countries having the highest yield gains of 20%. These yield changes result in <21% reduction in crop prices and <1% increase in GDP. The negative yield change in the USA indicates that even without CO_2 fertilization, this region benefits from a higher level of climate change[2] in term of crop yields in the period of 2061-2080. The mitigation effects are similar to the ones when CO_2 fertilization is included.

Comparing the climate and mitigation effects we find that, both with and without CO_2 fertilization, climate has larger effects on crop-related indicators, such as crop production and consumption, and cropland demand, while mitigation has stronger effects on the overall economy, i.e., GDP, reflecting the larger role of the energy sector in the overall economy. The mitigation effect on crop prices is less than half as large as the climate effect for most regions, reflecting the importance of both land and energy inputs to agricultural production, but the more direct effect of land productivity on production. Generally speaking, if CO_2 fertilization effects are included in the analysis, both mitigation and climate have negative impacts on the economy when changing from RCP8.5 to 4.5: decreased yields (up to -10%), reduced crop production and consumption, higher crop prices (up to 17%) and lower GDP (up to -7%). However, if CO_2 fertilization effects are not included, mitigation and climate drive the economy in different directions. The net effect depends on which impact is larger: the higher yield (up to 20%) in RCP4.5 relative to RCP8.5 leads to a positive net effect on crop production and consumption and a decrease in crop prices (-19%), all of which are driven primarily by climate effects, while the net effect on GDP (-6%) is negative because the mitigation effect dominates.

3.4 Development Pathway vs. Climate

To put the impacts of climate change and mitigation in context, it is useful to compare future outcomes for the same socioeconomic development pathway but different climates (as reported in the previous section) to outcomes for the same climate but different development pathways. To do this, we compare the difference between SSP5-8.5 and SSP5-4.5 (Fig.5) with the difference between SSP5-8.5 and SSP3HG-8.5 (Fig.6, with CO_2 fertilization).

The differences in outcomes due to alternative development pathways (Fig.6) greatly exceed those due to different climate (and mitigation) scenarios (Fig.5). Based on the SSP storylines (O'Neill et al 2015), SSP5 includes high economic growth, rapid technological change, low population growth, and a fossil-driven energy system. When implemented in iPETS, this SSP implies rapid growth in labor productivity, technological change that increases land productivity, and substantial growth in income and consumption. In contrast, the SSP3HG storyline envisions a more fragmented, slower growth development pathway with high population growth and slow technological change. Its associated iPETS scenario has slower growth in the productivity of labor and

[2] Both RCP4.5 and RCP8.5 without CO2 fertilization cause crop yields in USA to decrease, however, RCP4.5 induces higher yield loss than RCP8.5 in USA in 2061-2080. In other time periods, yield under RCP4.5 is higher than RCP8.5.

land (relative to SSP5), and much slower growth in income and consumption. These differences in societal trends lead to large differences in outcomes compared to climate effects. For example, comparing SSP3HG to SSP5 under the same climate (RCP8.5) (Fig.6), GDP is more than 40% lower for all regions, while mitigating from RCP8.5 to RCP4.5 in SSP5 reduces GDP less than 7% for all regions (Fig.5). Similarly, cropland demand is 36% higher in SSP3HG compared to SSP5 under RCP8.5 (due to larger population and lower land productivity), while cropland demand decreases less than 4% when mitigating to RCP4.5 within SSP5 on global average. Yield itself is 10-40% lower in SSP3HG than in SSP5 (for the same climate), a substantially larger difference than induced by the different climate outcomes. The relative effects of climate and development pathway are not dependent on whether or not CO_2 fertilization is included.

4 Conclusions and Discussion

This study analyzes the economic impacts of yield changes due to climate change. Our results show that the sign of the climate effect depends on whether CO_2 fertilization effects on crops are included or not. Climate change with CO2 fertilization as simulated in CLM has positive impacts on crop yields and the economy, and therefore if climate is mitigated from RCP8.5 to RCP4.5, crop yields decrease by up to 10% with negative impacts on the economy: reduced crop production, higher crop prices and lower GDP. Combined with the generally negative impacts from the mitigation effort, GDP is reduced by 7% and crop prices increase up to 17%. However, if CO_2 fertilization is not included, the net effect of climate on crop yields and the economy is negative, and mitigating from RCP8.5 to 4.5 would increase yields up to 20%, offsetting some of the negative impacts from emissions mitigation and resulting in lower crop prices by up to 19% in most regions.

The agricultural impacts of climate change examined here (in percentage terms) do not depend sensitively on the future development pathway. However, this is likely due to the aggregate metrics we use to measure such impacts. Other studies that examined impacts in terms of risks of hunger and that better accounted for more vulnerable segments of the population (Fisher et al., 2005; Hasegawa et al. 2015) find that climate impacts are in fact quite sensitive to the development pathway.

We find that the implications of different socioeconomic development pathways for outcomes related to agriculture are much larger than the implications of different levels of climate change, consistent with previous findings (Fisher et al. 2005; Schmidhuber and Tubiello 2007; Hasegawa et al. 2013). Outcomes for GDP, prices, and land use are 4-21 times more sensitive to the development pathway than to the climate conditions assumed here on global average and 0.3-113 times on regional levels.

As a first exercise to link CLM and iPETS for agricultural impact analysis, there are some caveats and key directions for future work. In the CLM analysis of climate and CO_2 impacts on yield, key areas for improvement include accounting for effects of other factors on yield, including extreme heat, flood events, pests and disease, and ozone damages. Incorporating these factors would likely lead to more negative yield impacts than found here and remains a research frontier for the field. CLM models photosynthesis process of C3 crops based on Farquhar et al. (1980) and the current version CLM4.5 has an updated parameterization based on literature synthesis and theoretical advances (Bonan et al. 2011). The CO_2 fertilization effect in CLM4 (a former version of CLM without the parameterization update) has been compared with two Free-Air CO2 Enrichment (FACE) sites and the net primary productivity (NPP) response to CO2 elevation from CLM4 matches observations reasonably well for one site but not the other (Zaehle et al. 2014). However, the comparison is only for forests. There are no studies comparing CLM CO_2 fertilization effects on crop yields with observations but the yield response to climate change with CLM4.5 is within the range in the literature as discussed above.

Nevertheless, the crop yield response to CO_2 concentrations varies widely across different crop models (Rosenzweig et al. 2014) and remains a crucial field for research. In addition, the treatment of management practices, including fertilizer and irrigation, is currently limited. CLM has only two options for nitrogen fertilizer application: none or the current North American level. In this study, we used linear interpolation to estimate yields for scenario-based assumptions about changes in fertilizer application rates over time, but this approximation approach also affects the magnitude of the interaction effects between CO2 fertilization and nitrogen fertilizer application. Regarding irrigation, CLM uses as much water as necessary without considering local water shortages. Climate-induced changes in aggregate irrigation water demand are modest in these scenarios (Levis et al. this issues), but this still remains an important area for improvement.

In the economic responses to yield changes from iPETS, a key area for improvement is better accounting for multiple adaptation possibilities, such as changes in crop types, management and trade. Currently, iPETS only models one aggregate crop type which limits the possibilities for changing crops to avoid climate damages or increase climate benefits. Management practices are not explicitly modeled, and the trade system in iPETS is based on the commonly used Armington (1969) assumption. While in widespread use, the Armington assumption has critics (e.g., Li et al 2015) and either a more- or less-responsive trade system would change the economic consequences of a given climate outcome. More generally, there is uncertainty in the iPETS response to yield changes due to uncertainty in parameter values beyond those affecting trade, for example in the production and consumption components of the model. An analysis of the robustness of the results presented here would be valuable future work, but is beyond the scope of this paper.

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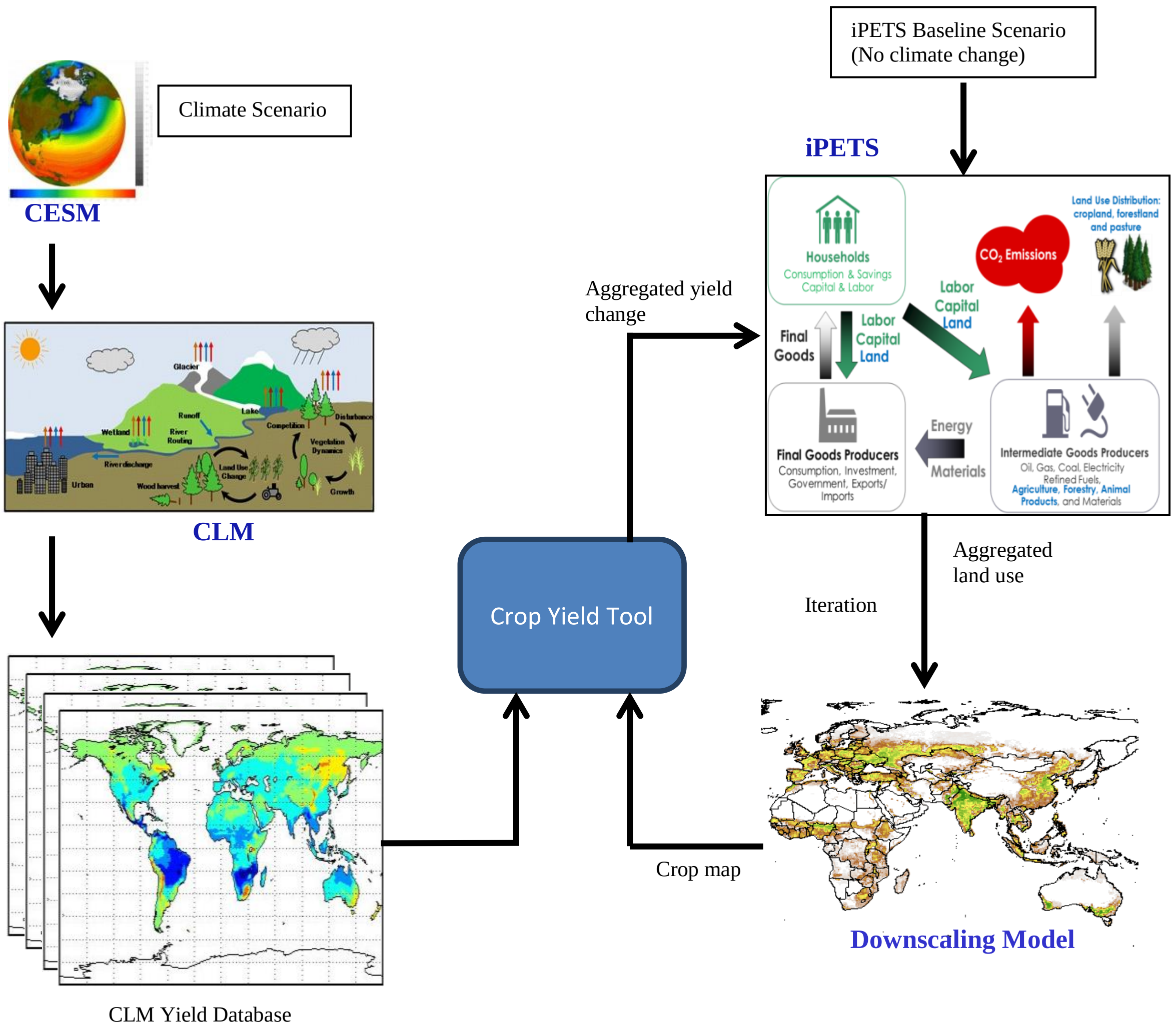

Fig. 1

Linkage between CLM and iPETS. CESM provides the climate scenario; CLM produces the yield database that contains yield information at every grid cell for different climate and management scenarios; the downscaling model produces spatial cropland distributions derived from the aggregated cropland areas from iPETS; iPETS is the economic model used to evaluate the economic impacts.

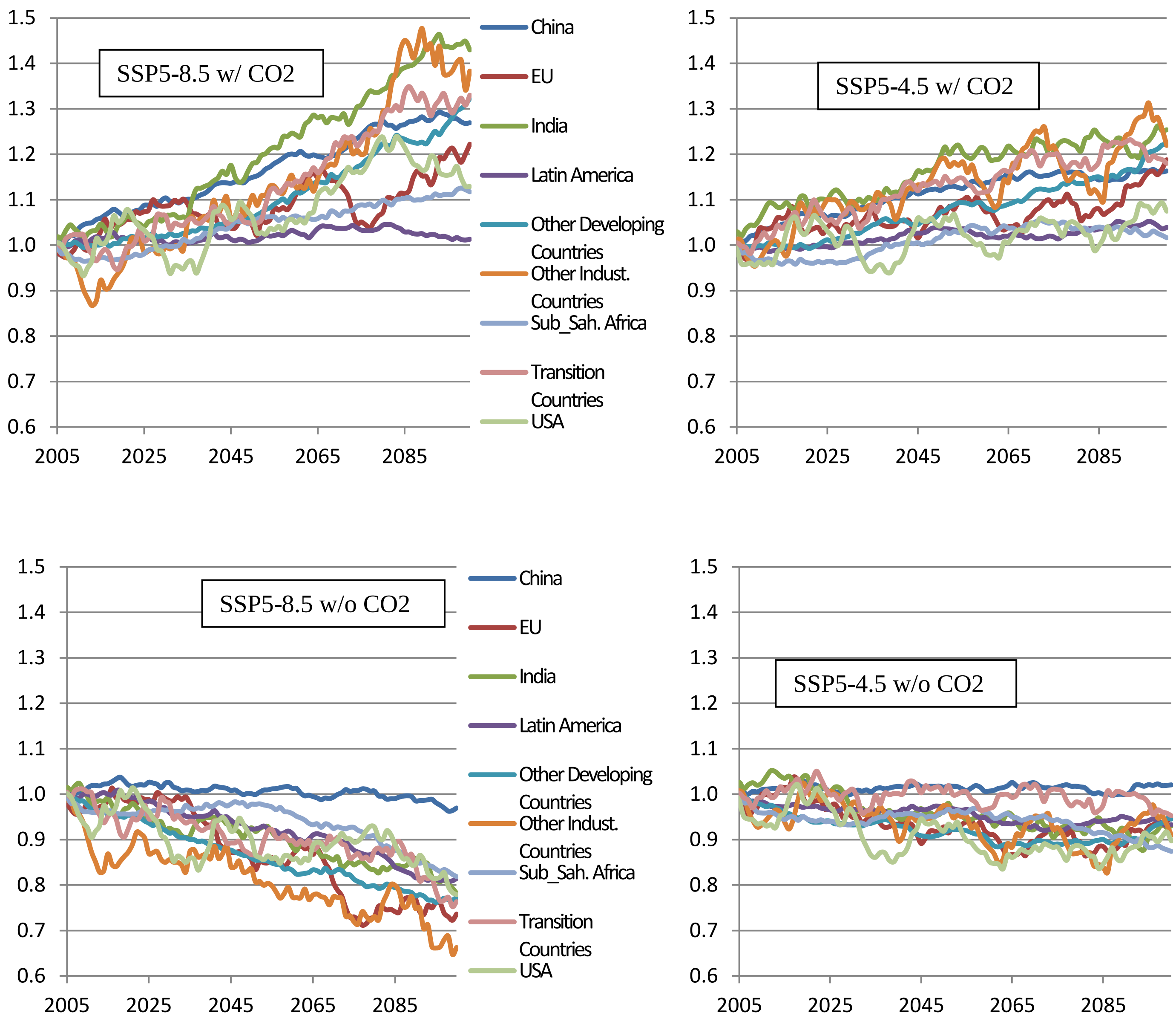

Fig.2

Aggregated yield changes for iPETS regions are calculated by subtracting yield with constant climate from yield with climate change at the same time period, with yield results from CLM in each case adjusted for management and smoothed to reduce annual variability. Differences are expressed relative to the absolute value of yield for each region assumed in iPETS at base year (2004), with those yields normalized to 1. The constant climate results in CLM are produced by recycling the CESM climate every 20 years (1985-2005) (see ESM7 for details). Results for SSP3HG are similar to those for SSP5 and are shown in ESM Fig.10.

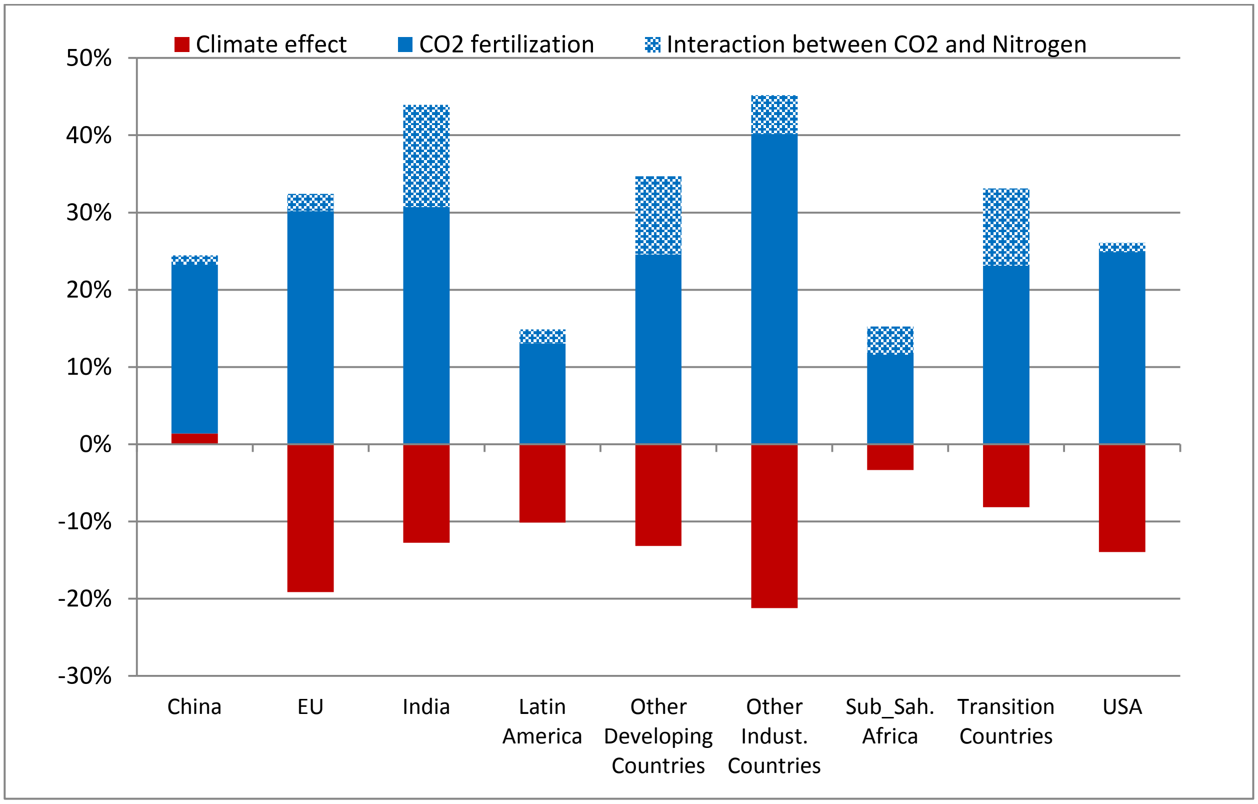

Fig 3.

Components of average regional yield change 2061-2080 for SSP5-8.5 with CO_2 fertilization. Red solid bars show climate effects due to temperature and precipitation on yield changes; blue solid bars show the pure CO2 fertilization effects and blue patterned bars show the interaction effects between CO2 fertilization and nitrogen fertilizer. The combined effects from blue solid bars and patterned bars are the overall CO2 fertilization effects.

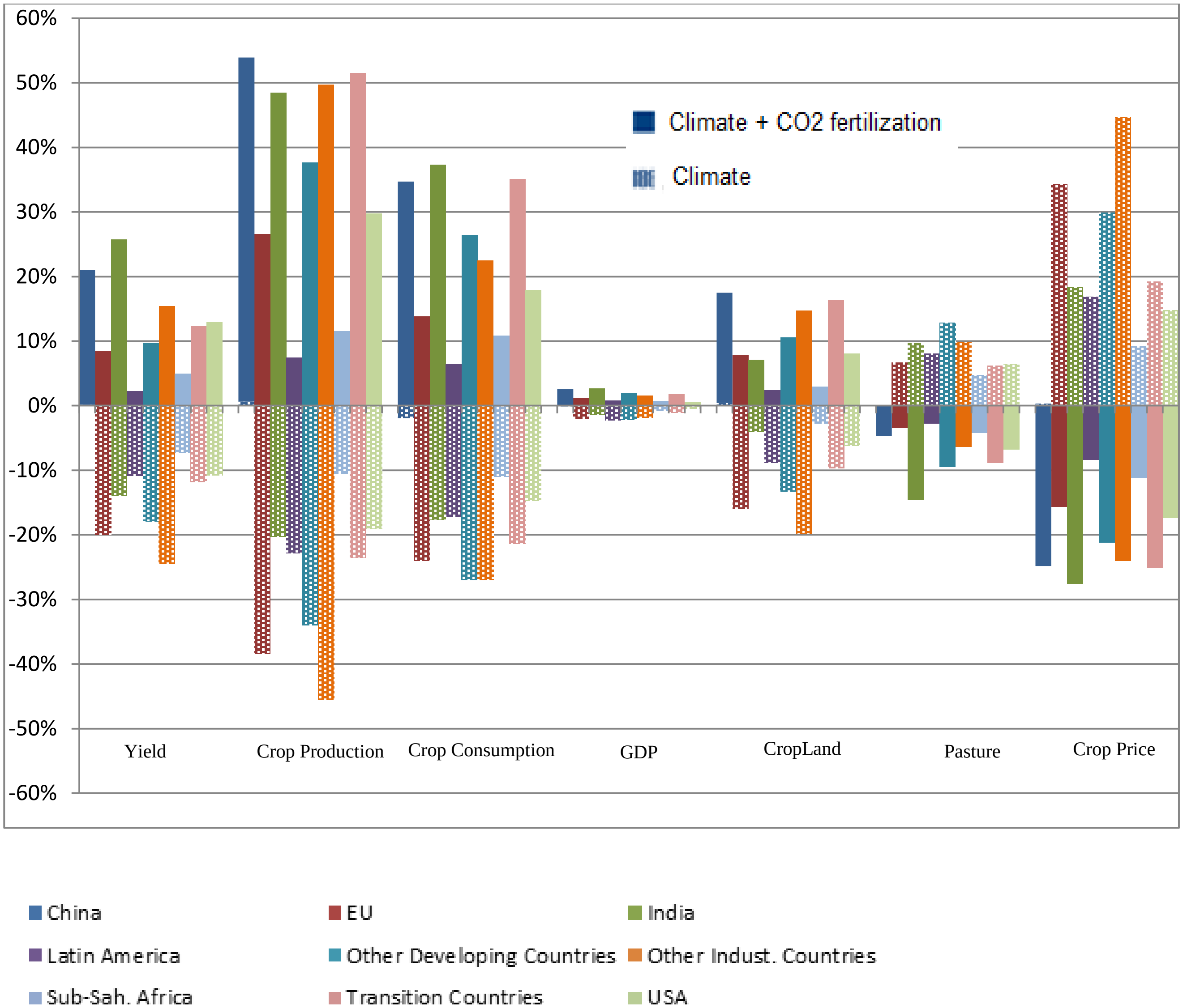

Fig.4.

Climate impacts on the economy (average 2061-2080) for SSP5-8.5, expressed relative to outcomes in SSP5-8.5 scenario without climate change. Solid bars represent impacts from climate and CO_2 fertilization and patterned bars show impacts from climate due to temperature and precipitation change.

Fig.5.

Avoided impacts on the economy (average 2061-2080) in SSP5-4.5 compared to SSP5-8.5, expressed relative to outcomes in SSP5-8.5. The top panel shows overall climate impacts with CO_2 fertilization and the lower panel shows climate impacts without it. Solid bars show climate impacts alone and the patterned bars show mitigation effects alone.

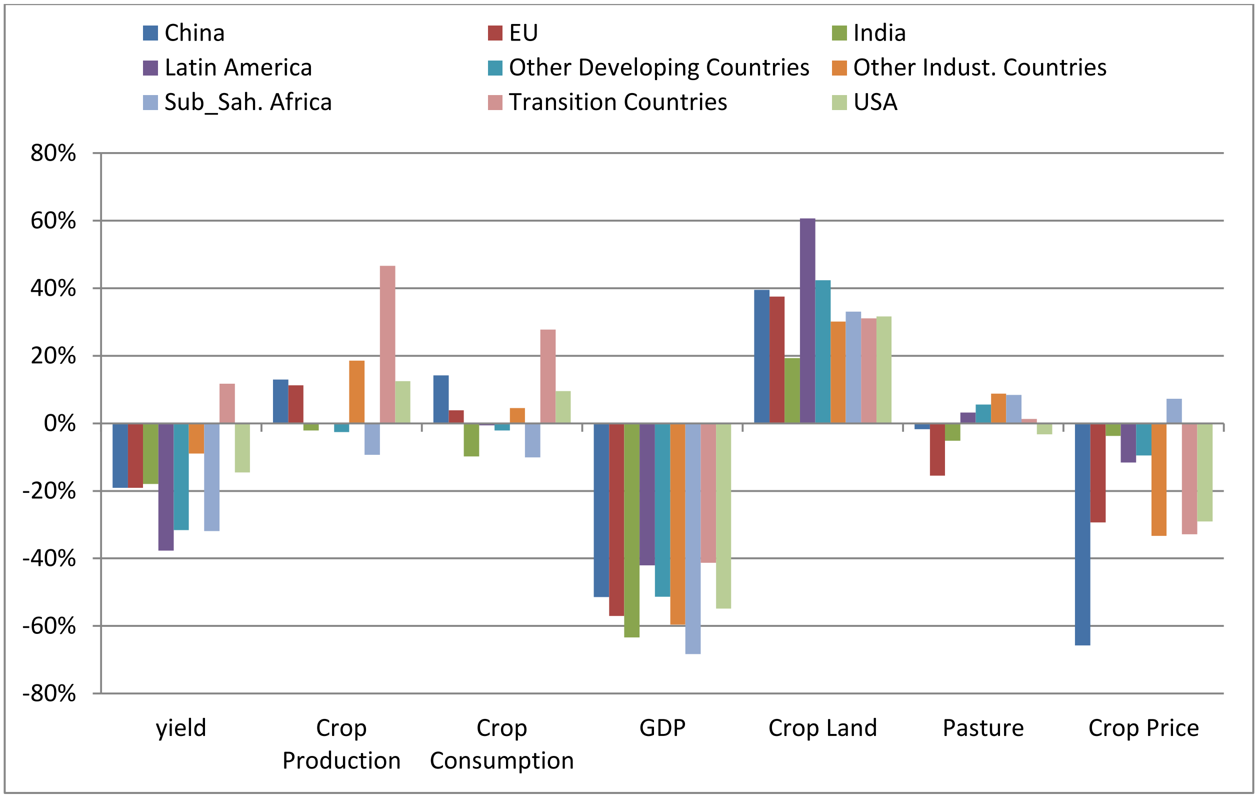

Fig.6

Impacts of different development pathways on the economy (average 2061-2080), expressed as the difference between outcomes for SSP3HG-8.5 compared to SSP5-8.5, relative to values for SSP5-8.5. All results include the effects of climate impacts with CO_2 fertilization.

Avoided economic impacts of climate change on agriculture: Integrating a land surface model (CLM) with a global economic model (iPETS)

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1 iPETS Model Structure

The integrated Population-Economy-Technology-Science (iPETS) model is an integrated assessment modeling framework that links a global energy-economic growth model, the Population-Economy-Technology (PET) model (Dalton and Goulder 2001; Dalton et al. 2008; O'Neill et al. 2010, O'Neill et al. 2012) with a one-dimensional model of global climate and greenhouse gas cycles, the Integrates Science Assessment Model (ISAM; Jain et al., 1996; Harvey et al. 1997; Wigley et al. 1997). In this analysis, we do not use the ISAM component of iPETS.

The iPETS model is a forward-looking multi-region, multi-sector global computable general equilibrium (CGE) model. The current standard configuration of the model has nine global regions and the region map (and definition of regional abbreviations) is shown in Fig.1. In each region, there are nine sectors producing intermediate goods and six consumption goods. Sectors producing intermediate goods include five energy sectors [Oil (E1), Gas (E2), Coal and biomass (E3), Electricity (E4) and Refined fuel (E5)], three land use sectors [Crops (Crop), Animal products (AP) and Forestry (FOR)], and Other Production (OP). Consumption goods include three energy consumption goods (Electricity, Coal and Biomass, and Other energy), Food, Transportation, and Other Consumption. Households in the iPETS model are represented by a single, infinitely-lived representative household in each region that has perfect foresight. Heterogeneity and compositional change due to demographic change, including urbanization, aging, and changes in household size, are captured in the model by making labor supply and consumption preferences of the representative household time-varying functions of the underlying changes in demographic composition, based on recent household survey data describing the economic characteristics of different household types. Income effects on consumption are included through exogenous relationships between income and these preferences and iterating between model solutions and the implications of income growth for preferences (O'Neill et al. 2012).

The structures of intermediate goods production and of consumption are shown in Fig.2. At each nest level, the production function follows the standard Constant Elasticity of Substitution (CES) function form: $Y = \gamma(\sum_i \alpha_i X_i^{\rho})^{1/\rho}$, where Y is the output, X_i is the i-th input, α_i is the share parameter for the i-th input and γ is the scaling factor for the production process. Parameter $\sigma = \frac{1}{1+\rho}$ is the elasticity of substitution. The main data requirements are Input-Output tables based on the GTAP 7.0 Database (Narayanan and

Walmsley2008) developed by Global Trade Analysis Project (GTAP) supplemented by energy balance data from IEA (Fuchs et al., 2009), and household preferences based on various household survey data (Zigova et al., 2009).

iPETS produces energy-related emissions of CO_2, but does not produce emissions of CO_2 from land use or emissions of non-CO_2 gases or aerosols. Previous versions of iPETS (Dalton and Goulder 2001; Dalton et al. 2008; O'Neill et al. 2010, O'Neill et al. 2012) didn't explicitly include land. In this version, land use is explicitly modeled and the three land use sectors (Crops, Animal Products and Forestry) are split out from the previous Other Production sector. As seen in Fig.2, managed land (L) is converted from unmanaged land (S) by combining it with Other Production (OP) inputs. This approach allows producers to bring new land into production (or take it out of production) when needed. Although iPETS can incorporate multiple land types differentiated by physical characteristics, in this study only one land type is included (i.e., all cropland is treated equally).

2 iPETS baseline calibration

As discussed in the main text the iPETS model is first calibrated to reproduce the results of existing scenarios based on SSP3 and SSP5 before applying climate effects on yield to estimate impacts on the agricultural system. We calibrate to outcomes projected by the Global Change Assessment Model (GCAM) using SSP-based scenario outcomes provided to us by the GCAM group in July 2014 (Calvin et al. in prep). The variables that we calibrated to are GDP, energy use (oil, gas, coal, refined fuel, electricity and renewable electricity production), conversion efficiencies of the electricity and refined fuel sectors, land use (cropland, pasture, and forest), and crop yields for the nine iPETS regions from 2005 to 2100. To define GCAM-based targets for these variables, we apply the growth rates for these variables from GCAM (aggregated to the 9 iPETS regions) to iPETS base year values, which are based on the GTAP 7.0 Database. To achieve these targets in iPETS, we adjust the following model parameters (including their pathways over time) in each region: labor productivity; partial factor productivities of coal, gas, electricity, refined fuel, cropland, pasture and forestry land to all production process; partial factor productivity of electricity to electricity production, and of coal to refined fuel production; and total factor productivities of electricity, refined fuel and cropland. The calibration produced outcomes for targeted variables that deviated by less than 1% averaged over the period 2005-2100, with maximum deviations in any given year of 2% for GDP, 15% for (fuel-specific) energy use, 10% for land use by sector and 4% for crop yield. Variables that were not specifically calibrated to GCAM targets had larger deviations, the largest being for biomass use which differed by up to 30% in a given year. Global CO2 emissions from energy use were not explicitly targeted but were within 5% of GCAM values on average over the century.

Some key variables for this application (GDP, cropland areas and crop yields) for both iPETS model and GCAM are shown in Fig.3 for the no-climate baseline scenarios SSP3 and SSP5 (note that differences between models are due primarily to differences in assumed values in the initial year, which are controlled for in the calibration process). Comparing the two socioeconomic pathways, SSP5 has much higher GDP and also higher yields in most regions. As a result of higher yields, as well as of much lower population growth, the demand for cropland in SSP5 remains relatively constant over the next century while in SSP3, high population growth and slower yield improvements drive an approximate doubling of cropland in most regions.

3 SSP3HG scenario

In this study, we aim to assess avoided impacts in RCP4.5 relative to RCP8.5 for two different socioeconomic pathways (SSP5 and SSP3) and to compare impacts under a given climate outcome between the two SSPs. It is of particular interest to compare outcomes in a high forcing pathway (RCP8.5) across pessimistic (SSP3) and optimistic (SSP5) development pathways that vary in the challenges they present to adaptation. However, preliminary results from integrated assessment models quantifying emissions and radiative forcing scenarios based on the SSPs indicate that while forcing in an unmitigated baseline scenario based on SSP5 is consistent with RCP8.5, forcing based on SSP3 is not (IIASA 2015). This is also true for the GCAM scenarios to which we are calibrating. The GCAM scenario based on SSP3 reaches approximately 7W/m2 in 2100. In order to create an internally consistent scenario that combines SSP3 with RCP8.5, we construct a variant of SSP3 with higher CO_2 emissions from energy use (the type of emissions modeled in iPETS) that we estimate would be consistent with a scenario including all greenhouse gas emissions and short-lived climate forcers that reached a forcing level equal to the forcing level in 2100 achieved in the GCAM SSP5 scenario.

To estimate how much energy-related CO_2 emissions need to be increased relative to their levels in the GCAM SSP3 scenario, we first set a target for CO_2-related forcing that would be consistent with the SSP5 forcing level in 2100. To do this, we assume that non-CO_2 forcing is proportional to CO_2 forcing in the SSP3 baseline scenario. We made this assumption based on the strong correlation in GCAM results for all SSPs over time and in particular for SSP3 over time between non-CO_2 forcing and CO_2 forcing (ρ=0.80 for all SSPs and ρ=0.99 for SSP3 only), which was stronger than its correlation with other possible indicators like GDP (ρ=0.67 and ρ=0.99, respectively) or CO_2 emissions (ρ=0.80 and ρ=0.96, respectively). Based on this assumption, CO_2 forcing of 6.4 W/m2 in 2100 would be consistent with SSP5 total forcing in 2100.

We then convert the CO_2 forcing target into a target for cumulative CO_2 emissions using the relationship between cumulative emissions and CO_2 forcing in 2100 in GCAM across all five SSPs, which implies a target of 1850 GtC cumulative emissions from 2010-2100. We adjust this target to account for cumulative emissions from land use (assumed to be 80 GtC, as in the GCAM SSP3 scenario) and from industry (78 GtC, as in GCAM SSP3), leading to a target for cumulative CO_2 emissions from energy use of approximately 1700 GtC. For comparison, cumulative emissions are 1403 GtC in our original SSP3 scenario.

The increase of CO_2 emissions necessary to reach 1700 GtC cumulatively was achieved by increasing GDP through higher labor productivity; we therefore call this a higher growth (HG) variant of SSP3. This approach preserves the economic structure in our version of SSP3 with minimum changes. The annual GDP growth rate was increased by 0.37 percentage points after 2010 in all regions above the original SSP3 growth rate, leading to a 39% larger global GDP in 2100. Nonetheless, SSP3HG is still a low growth pathway relative to other SSPs, with per capita GDP considerably below all other SSPs (about 30% below SSP4, which is the second lowest scenario for GDP; Dellink et al., 2015). Thus we believe SSP3HG retains the essential nature of SSP3 as a development pathway with high challenges to adaptation and to mitigation. Preferences were assumed to change with this increase in per capita GDP, leading to a lower expenditure share for food. However due to overall income growth, global land use increases by 2.4% (10.7% increase in cropland, 12.3% increase in pasture land, and a 10.9% reduction in forestland).

4 RCP4.5 (4.5W/m2) no-climate mitigation scenarios

To generate no-climate scenarios that are consistent with the RCP4.5 radiative forcing pathway, we apply a global carbon tax to the unmitigated baselines (SSP5 and SSP3HG) in order to achieve specified cumulative emissions targets for each. In the original GCAM implementation of RCP4.5, cumulative 2010-2100 CO_2 emissions amount to 763 GtC (including 18 GtC from land use change;

Thomson et al. 2011).[1] We allow for about 60 GtC from land use change in SSP3-4.5, and zero net land use emissions in SSP5-4.5, which yields targets for cumulative emissions from energy use of about 700 GtC and 760 GtC in SSP3 and SSP5, respectively. This is similar to the amounts in the GCAM baseline scenarios for SSP3 and SSP5 because land use emissions are not accounted for in iPETS and thus a carbon tax does not increase the cost of land conversion relative to the baseline scenario. To implement a carbon tax to achieve these reductions, we follow the approach in the original GCAM RCP4.5: the carbon tax is increased at a fixed annual rate through 2080 and kept constant thereafter, leading to relatively stable emissions after 2080. We apply the carbon tax beginning in 2015 and increase it linearly until 2020 ($29.44 /tC in SSP3; $37.47/tC in SSP5), and then increase it 5% annually through 2080 to reach $550/tC ($150/tCO_2) in SSP3 or $700/tC ($190.90/tCO_2) in SSP5, after which it is held constant. These rates of increase (and stable levels after 2080) were found to produce the target cumulative emissions totals.

5 Cropland Downscaling Method

The downscaling model was developed by Meiyappan et al (2014). It is a dynamic statistical model based on cost minimization at the grid cell level with two primary components: one that tends to minimize the difference in the spatial distribution of cropland and pasture relative to the previous period, and a second that tends to allocate cropland and pasture to land that is most suitable in the current period. The suitability index is a function of both biophysical and socioeconomic factors, including climate and soil conditions, GDP, urban/rural population, etc. The model is calibrated to global historical data over the past 100 years, and successfully reproduces large-scale features of land use change over that period. For future projections, the model uses total cropland and pasture areas for each region from iPETS output, urban/rural spatial population projections from Jones et al. (this issue) that are consistent with the aggregate population projections for the SSPs; and climate projections from CESM for the two RCPs. Other variables are assumed constant at current values.

6 CLM Yield Database

The CLM Yield database was generated by ten idealized CLM model runs (Levis et al. this issue). All CLM plant functional types (eight crop types, both irrigated and rainfed: temperate corn, soybean, spring wheat-rye-barley2, sugarcane, rice, cotton, tropical corn, and tropical soybean; generic C3 and C4 crops, both irrigated and rainfed; and all grass and tree types) coexist in every grid cell. The ten model runs are listed in Table 1. Among these model runs, RCP8.5 and RCP4.5 climate scenarios are from the CESM CMIP5 runs (Lawrence at el. 2012). We use this single CESM ensemble member for each RCP because only this member of the larger ensembles available for these forcing pathways saved outcomes at sufficient time resolution to drive CLM. For the runs without CO_2 fertilization, the CO_2 level is fixed at 2005 level. The constant climate model runs use 1986 to 2005 climate repeated every 20 years over the century. With these model runs, we estimate crop yields of any combination of crop types under different management practices, with or without CO_2 fertilization and different climate scenarios with any crop maps. More details on the yield database can be found in Levis, et al (this issue).

[1] At the time of constructing the mitigation scenarios, mitigations variants of the SSPs were not yet available. We therefore used cumulative emissions from the original RCP4.5 study.
[2] Rye and barley parameterized as spring wheat.

7 Crop Yield Tool

The crop yield tool produces a time series for each iPETS model region of the aggregate climate impact on crop yield using a projected map of cropland area from the downscaling model and the CLM yield database. The crop yield tool must carry out the following tasks:

7.1 Choose grid cells from the yield database that are consistent with the maps of future crop area

7.2 Specify the mix of crop types assumed for each grid cell

We assume that the mix of crop types within each grid cell is the same as in the base year, i.e., the land area share of each crop is the same as in 2004. If new land is brought into production, the mix of crop types is assumed to be the same as in the closest grid cell in which cropland existed in the base year.

7.3 Specify irrigation and nitrogen fertilizer assumptions

We make assumptions about irrigation and fertilizer application that are consistent with GCAM baseline scenarios for SSPs 3 and 5. Irrigation is determined within GCAM in order to maximize producer profits (weighing costs of irrigation vs benefits of higher yields). The fraction of total cropland that is irrigated is relatively constant for both SSP3 and SSP5, with less than 10% change in all regions in the GCAM scenarios. We therefore assume that the fraction of irrigated land is constant at CLM base year (2005) values in both SSPs for all CLM crops at each grid cell. When cropland in a new grid cell is brought into production, we assume all cropland is rainfed which is consistent with the assumption in GCAM. Note that SSP3 has a substantial expansion of cropland over the century, so that the assumption of a constant irrigated fraction requires additional irrigation water. We implicitly assume there are no constraints on water supply for irrigation, since CLM does not constrain water for irrigation based on availability. Levis et al. (this issue) estimate climate-driven changes in irrigation water demand in CLM with current cropland allocation, finding it is relatively small, but do not evaluate demands in scenarios with cropland expansion.

Nitrogen fertilizer use is not explicitly modeled in GCAM. However, yield change in GCAM is calibrated to reflect FAO projections that have explicit assumptions about fertilizer use (Alexandratos and Bruinsma 2012). The FAO projections assume separate growth rates for 2005 to 2030 and 2030 to 2050. We assume fertilizer application follows the FAO projection in both SSPs, and that growth rates for 2050 to 2100 are the same as 2030 to 2050. The extended FAO projection of fertilizer application rates for the iPETS regions are shown in ESM Fig. 4. While differentiating fertilizer assumptions between the two SSPs would be preferable, GCAM assumptions about fertilizer application in the two scenarios are not explicit (rather, GCAM differentiates yield growth in the two scenarios based implicitly on assumed differences in fertilizer use and other factors). In the absence of a specific existing fertilizer scenario, we draw on the single FAO projection for both SSPs.

The assumptions for irrigation extent and fertilizer application rates are implemented in the analysis in different ways. The constant irrigation extent assumption is incorporated when aggregating gridded yield outcomes to regional yield (7.4), drawing on separate yield results for irrigated and rainfed crops. The fertilizer application rates are accounted for by adjusting regionally aggregated CLM yield results that correspond to either no fertilization or fertilization rates that are held constant at current North American levels (7.6).

7.4 Aggregate CLM gridded yield information into iPETS regions for single crop type accounting for irrigation assumptions

The regionally aggregated yield results assuming current crop mix and constant irrigation fractions for all simulations included in the CLM database are shown in Fig.5 and 6. Both RCP8.5 and RCP4.5 induce yield increases for most regions when CO_2 fertilization is included (5a, 5b) and the yield increase is more obvious in RCP8.5. There are small differences in yield between SSPs (SSP5 vs SSP3HG) for a given climate outcome mainly due to the larger cropland expansion towards marginal land under SSP3HG. Generally, the newly added land has lower yields compared to the current cropland. Simulations with nitrogen fertilizer have significantly larger yields for all regions.

Note that the CLM yields in Fig.5 and 6 are not comparable to the yield values for iPETS shown in Fig.3. We use CLM yields only to derive climate impacts on yields to apply to iPETS, as described in 7.7; absolute values of yields are not consistent between the two models, for several reasons. Base year values differ since yield is an outcome for CLM while for iPETS the base year value is from the GTAP 7.0 database. In addition the iPETS yields represent all crops, including fruits and vegetables, while CLM includes only eight crops. The trends in yield over time in CLM reflect only changes in climate, while in iPETS they incorporate SSP-specific assumptions about technological change and changes in management.

7.5 Smooth the aggregated yields from CLM.

iPETS was developed to project long-term trends, rather than short-term fluctuations. We therefore smooth the CLM yield information using a centered 10-year moving average. Since CLM simulations end in 2100, yields for 2095-2100 are increasingly one-sided. The yields with constant climate were treated differently. The constant climate simulations used 1986 to 2005 climate repeated every 20 years over the century. To avoid introducing periodic discontinuities due to the 20 year repetition, a single linear trend is fit for yields with constant climate over period 2005-2100. on the yields with constant climate.

7.6 Adjust yields with the fertilizer application assumption: FAO fertilizer application rates

The CLM database includes simulations with two assumptions about nitrogen fertilizer: with or without. When nitrogen fertilizer is applied, each crop at every grid cell receives the current North American nitrogen fertilizer application rate based on Potter and Ramankutty (2010). Fig.7 compares the CLM fertilizer assumptions by region to FAO data, indicating that CLM under-fertilizes China, EU and USA while over-fertilizing all other regions.

We derive yields that are consistent with the current and projected FAO fertilizer rates by assuming that the yields from CLM are linearly correlated with fertilizer application rates if the CLM fertilizer rate is less than FAO value. An experimental CLM run shows that the current fertilizer application rates in CLM saturate the land, i.e., additional fertilizer application won't change the crop yield from CLM. So when the CLM fertilizer rate is higher than the FAO value, we keep the CLM yield value unchanged even if the projected FAO fertilizer rate increases. ESM Fig.8 illustrates the relationship used to adjust CLM yields for consistency with FAO data and projections. Adjusted yields are shown in Fig.9.

7.7 Calculate the yield change for each climate scenario

After adjustment for management, the yields with constant climate are subtracted from the yields with climate change to derive the climate impacts on yield for RCP4.5 and RCP8.5 with both baselines: SSP5 and SSP3HG. We then normalize yield changes to 1.0 in 2004. The normalization put the yield changes in the form necessary for application to the iPETS model, where it is implemented as a change in total factor productivity in the crop sector. In iPETS, productivity parameters represent relative changes compared to base year (2004). The normalization procedure follows the formula:

$$\Delta y_t = \frac{\left(y_t^C - y_t^{NC}\right) - \left(y_{2004}^C - y_{2004}^{NC}\right)}{y_{2004}^{NC}} + 1$$

where y_t refers to yield in time period t, superscript C refers to with climate impact and NC refers to no climate impact, i.e., constant climate. All yield values refer to the yields from CLM that have been smoothed and adjusted for management. The final yield changes that are applied to iPETS for SSP5 are shown in Fig.2 in main text and SSP3HG in Fig.10 .

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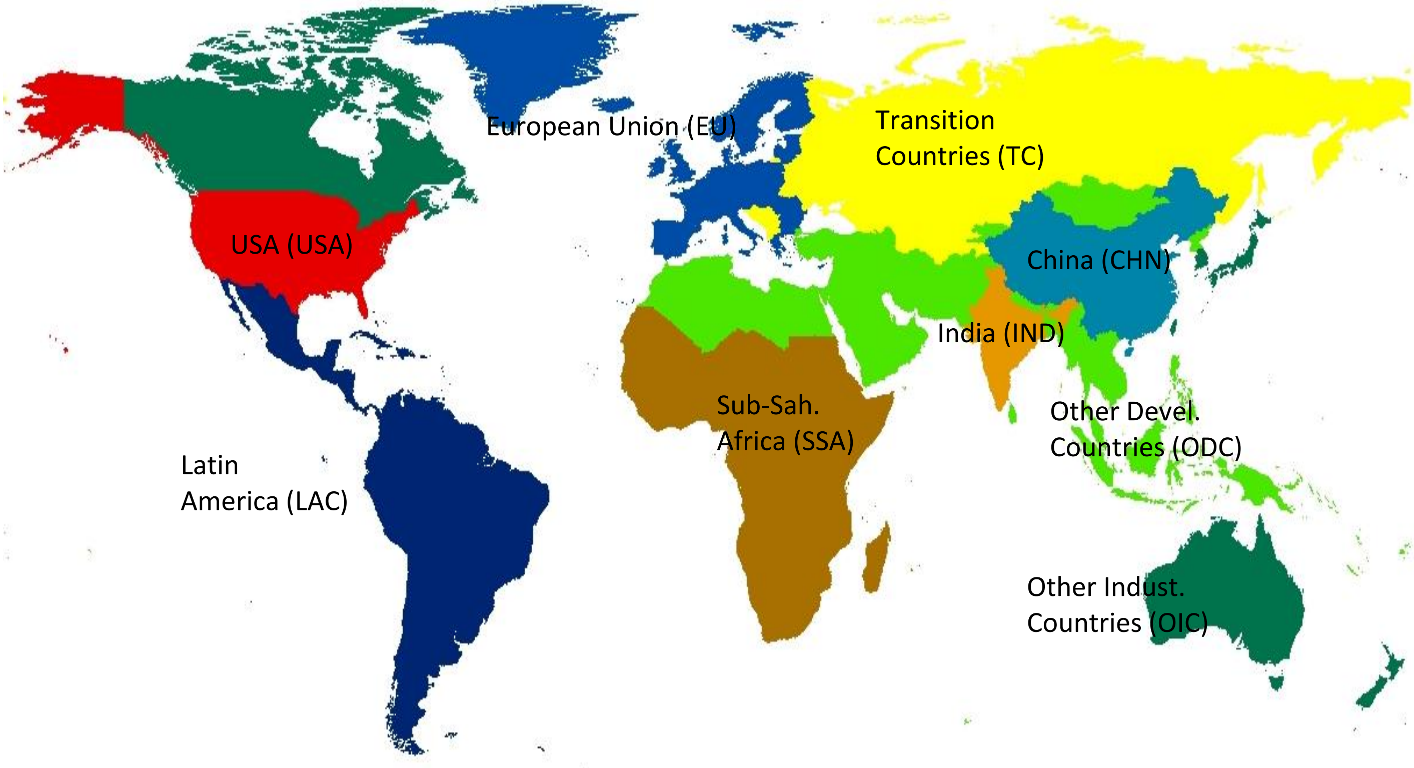
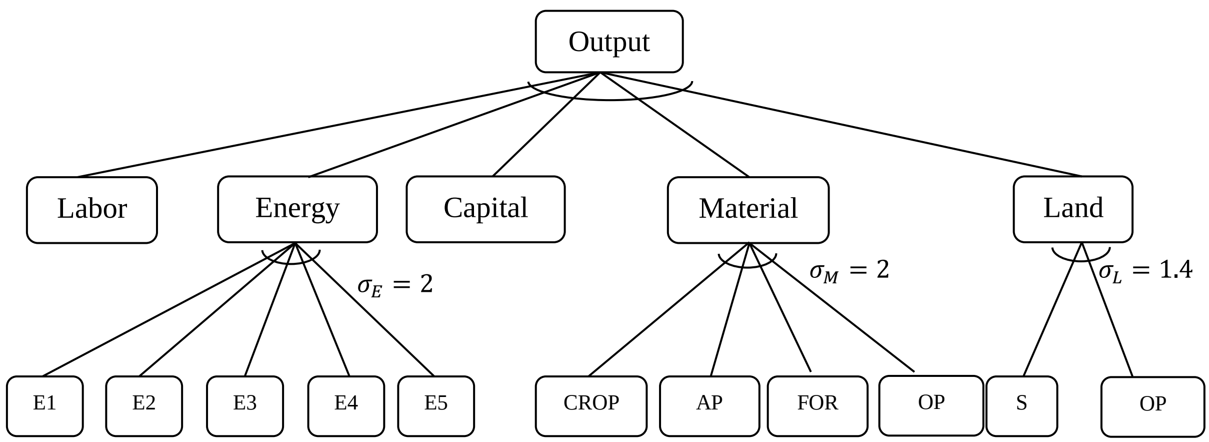


Fig.1
iPETS model region map. The acronym for each region is in parentheses.

(a)



(b)

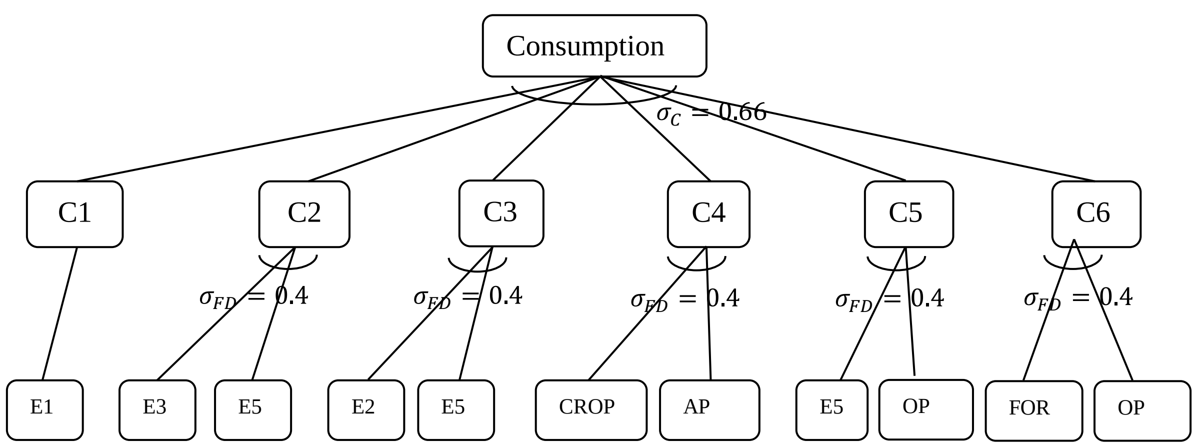
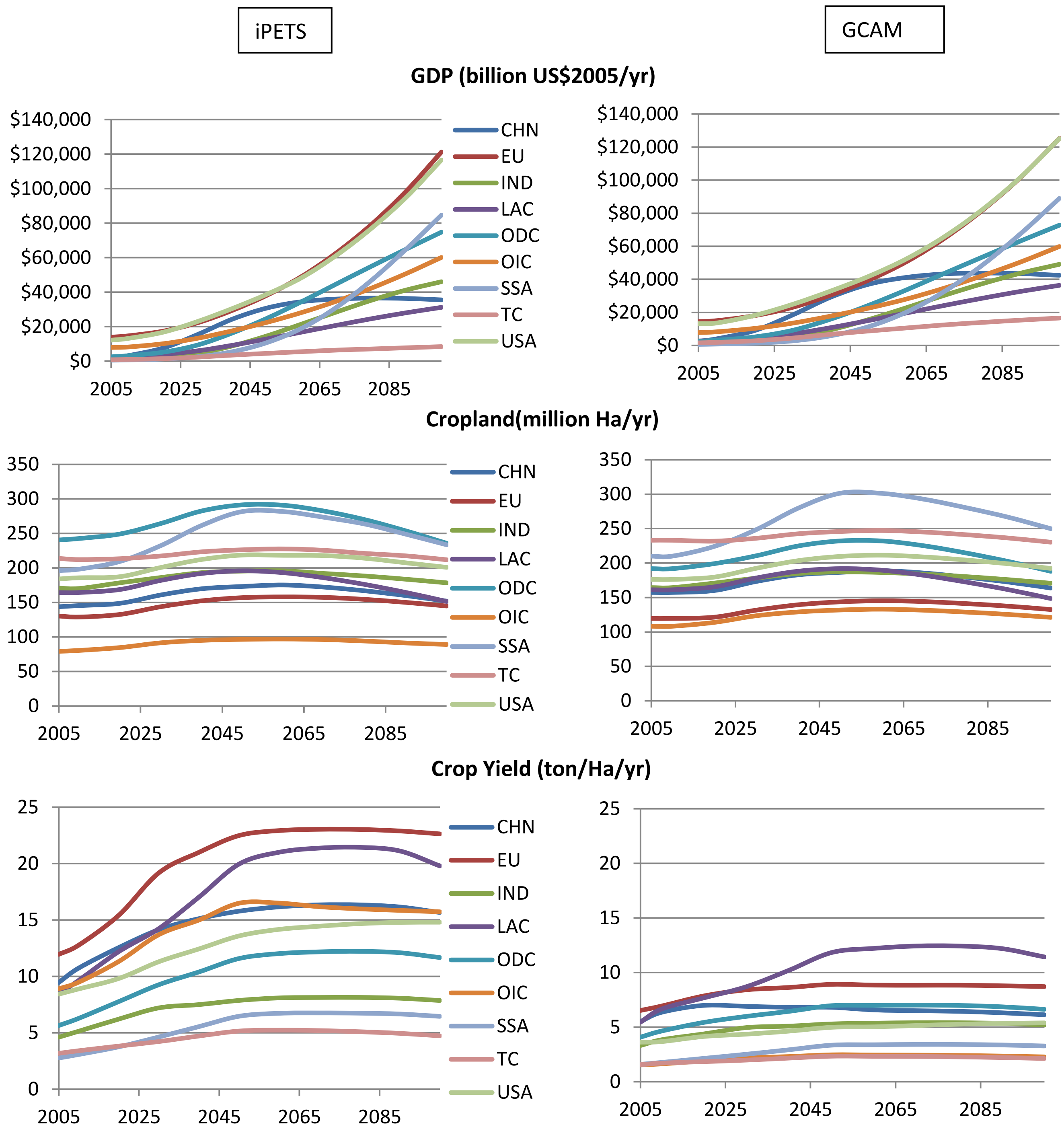


Fig.2

iPETS model nesting structure for production (a) and consumption (b). σ is the elasticity of substitution. Sectors definition: E1: Oil, E2: Gas, E3: Coal and biomass, E4: Electricity E5: Refined fuel, Crop: Crops, AP: Animal products, FOR: Forestry, OP: Other Production, C1: Household Electricity, C2: Household Coal and Biomass, C3: Household Other Energy, C4: Food, C5: Transportation, and C6: Other Consumption.

(a)


iPETS
GCAM
GDP (billion US$2005/yr)
$140,000
$120,000
$100,000
$80,000
$60,000
$40,000
$20,000
$0
2005
2025
2045
2065
2085
CHN
EU
IND
LAC
ODC
OIC
SSA
TC
USA
Cropland(million Ha/yr)
350
300
250
200
150
100
50
0
Crop Yield (ton/Ha/yr)
25
20
15
10
5

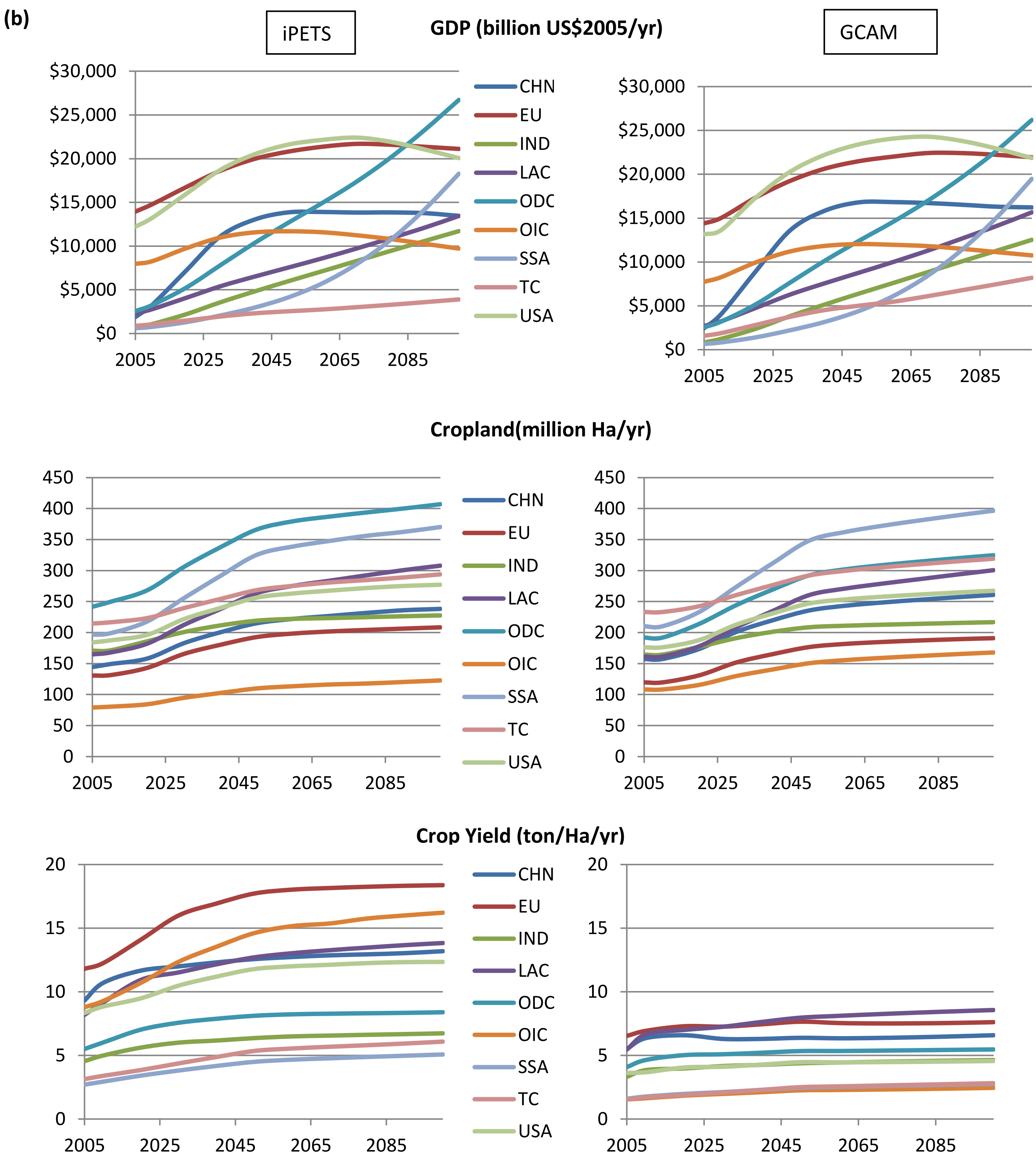


Fig.3

Key Variables for Baseline Scenarios for (a) SSP5 and (b) SSP3, iPETS vs. GCAM. Note differences between models are due primarily to differences in assumed values in the initial year. See Fig.1 for region definitions.

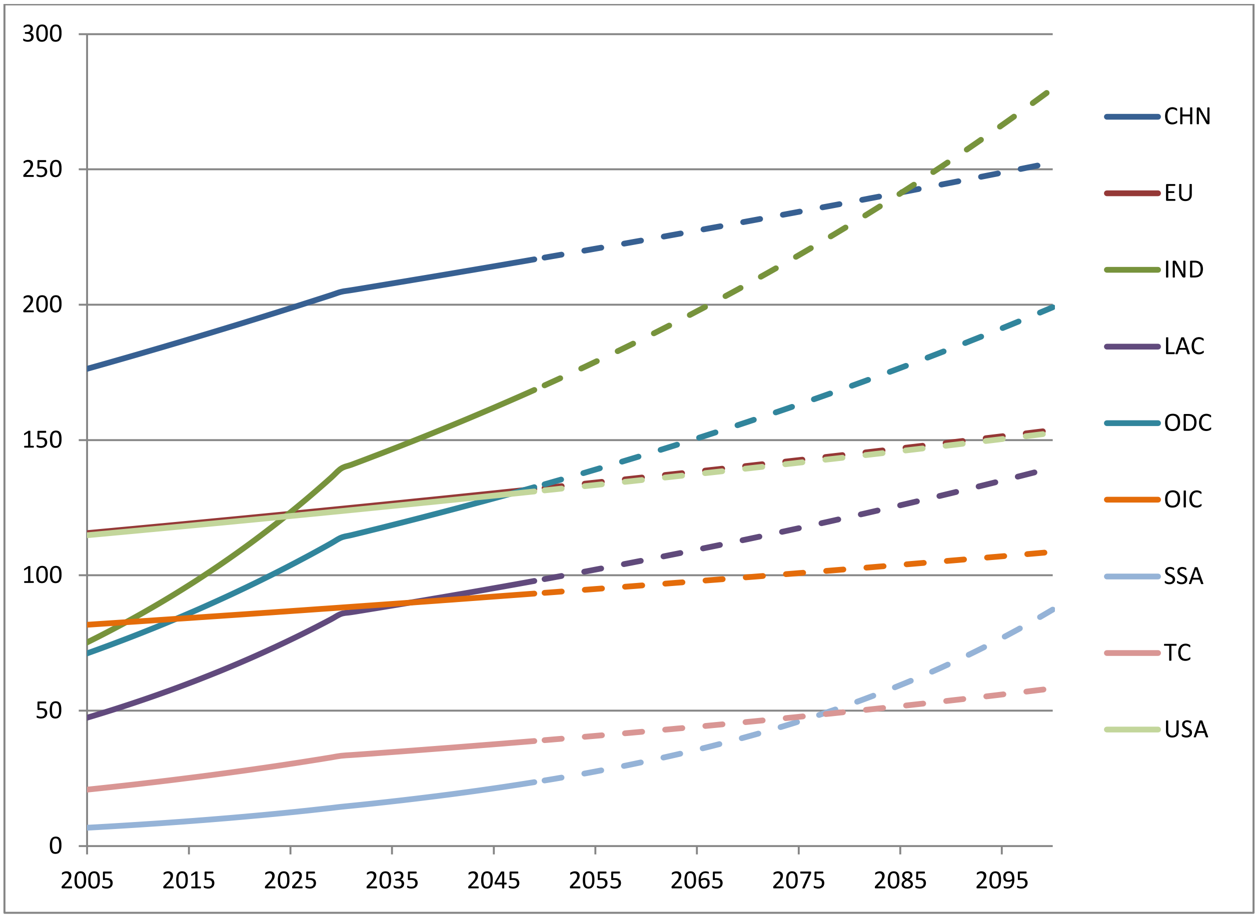


Fig.4

Fertilizer Application Rates (kg/ha) Projected by FAO (Alexandratos and Bruinsma 2012). Dashed lines are extensions from FAO projections based on the same growth rates from 2030-2050. See Fig.1 for region definitions.

(a)


RCP 8.5 w/ N Fertilizer
RCP 8.5 w/o N Fertilizer
RCP 4.5 w/ N Fertilizer
RCP 4.5 w/o N Fertilizer
Constant Climate w/ N Fertilizer
Constant Climate w/o N Fertilizer
0 1 2 3 4 5 6 7 8
2005 2025 2045 2065 2085
CHN
EU
IND
LAC
ODC
OIC
SSA
TC
USA

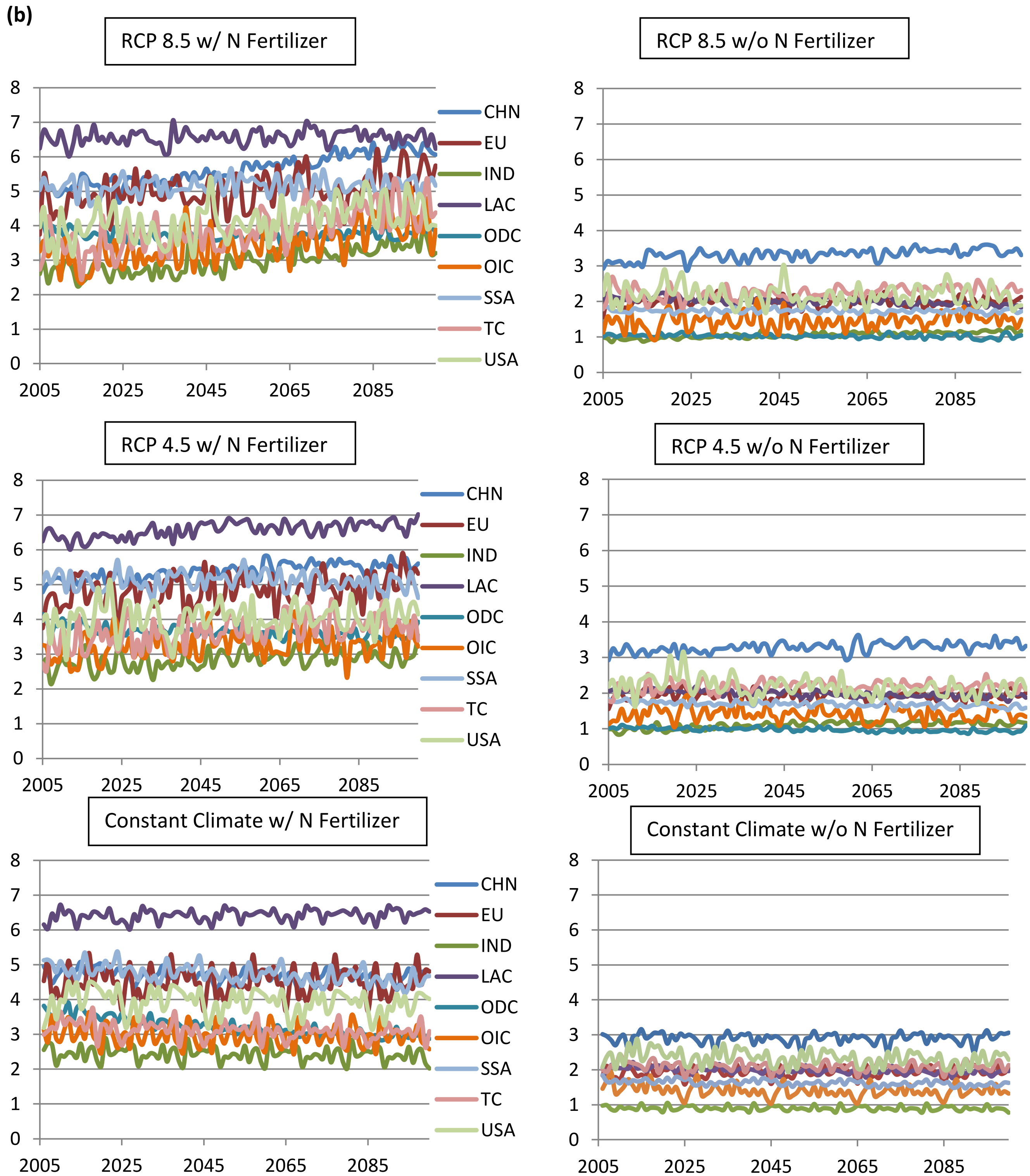
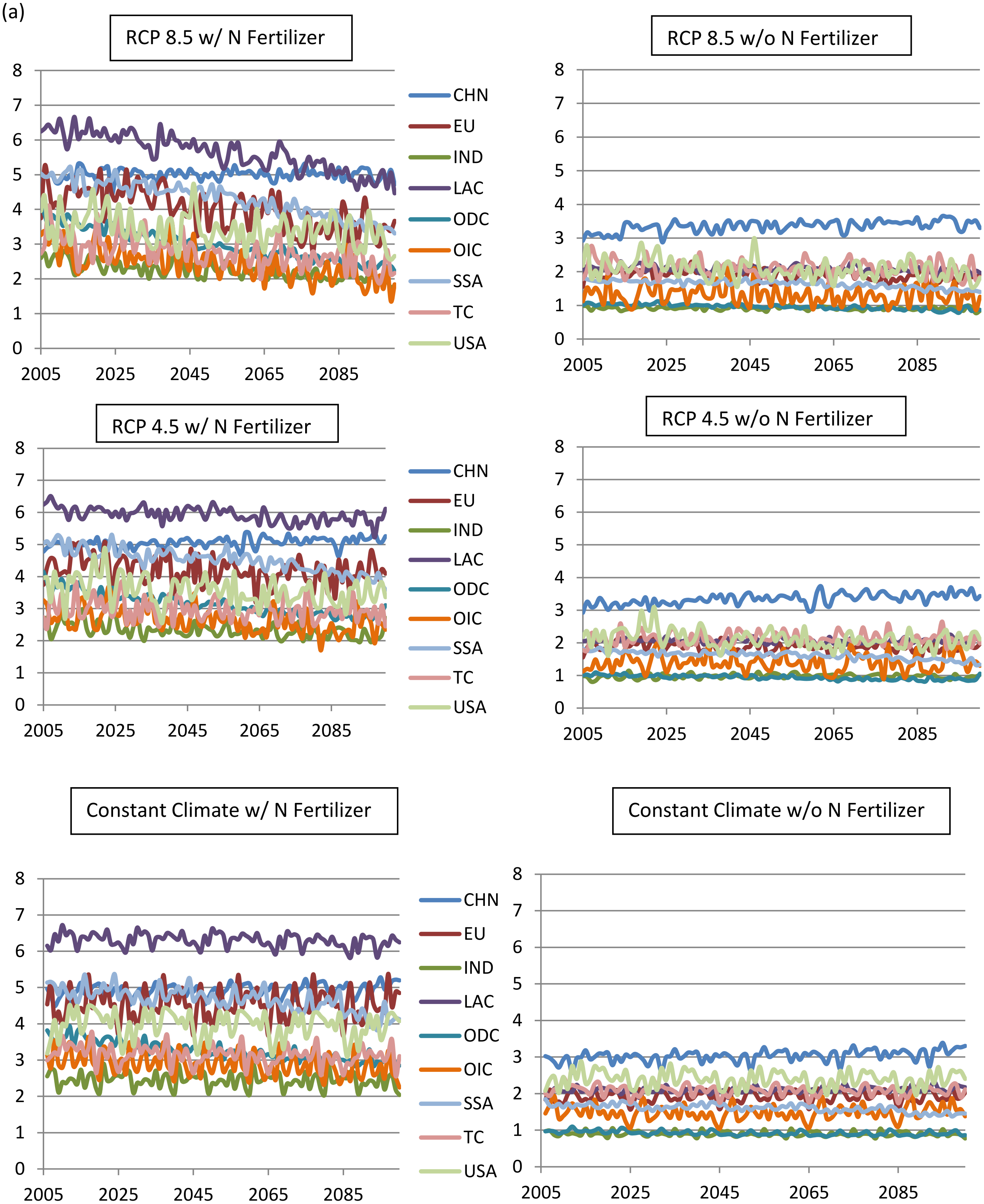


Fig. 5

CLM yields aggregated into iPETS regions for SSP5(a) and SSP3HG(b) cropland use with CO2 fertilization. See Fig.1 for region definitions.

(a)


RCP 8.5 w/ N Fertilizer
RCP 8.5 w/o N Fertilizer
RCP 4.5 w/ N Fertilizer
RCP 4.5 w/o N Fertilizer
Constant Climate w/ N Fertilizer
Constant Climate w/o N Fertilizer
0
1
2
3
4
5
6
7
8
2005
2025
2045
2065
2085
CHN
EU
IND
LAC
ODC
OIC
SSA
TC
USA

(b)

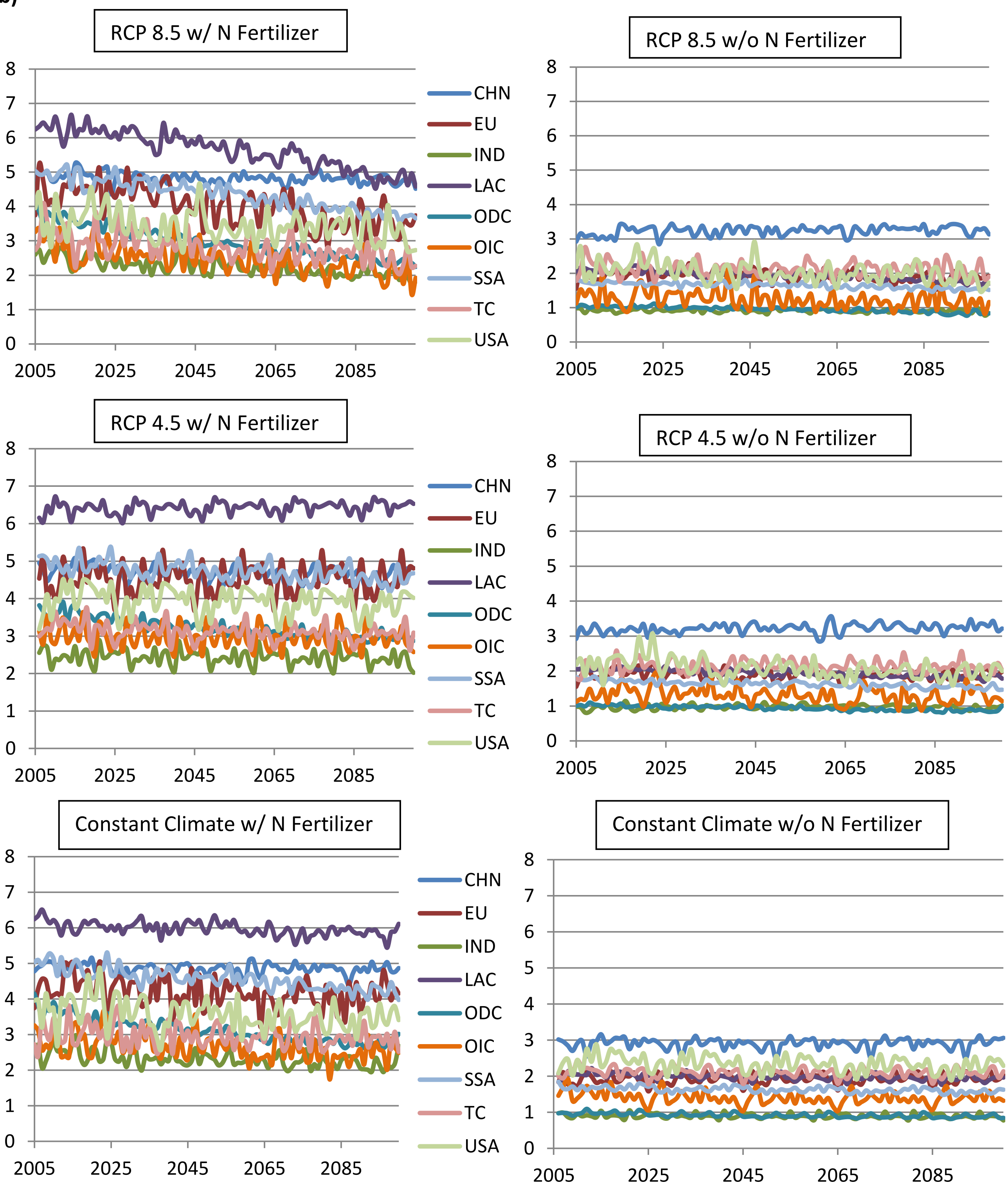


Fig.6

CLM yields aggregated into iPETS regions for SSP5(a) and SSP3HG(b) cropland use without CO2 fertilization. See Fig.1 for region definitions.

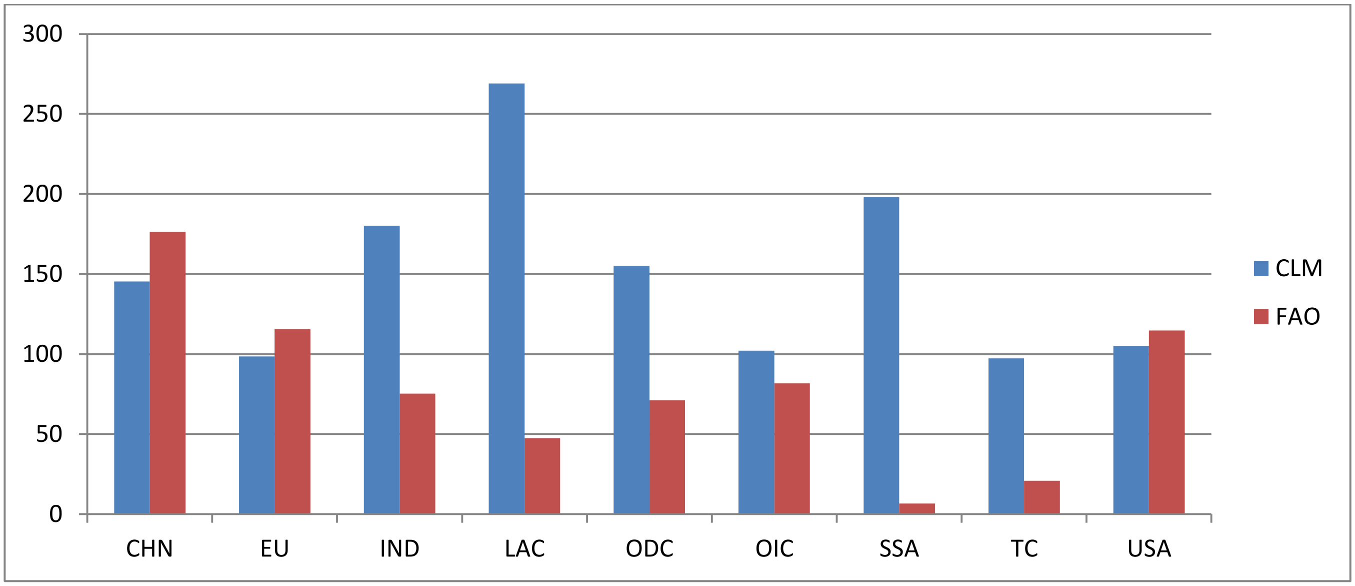


Fig.7
Fertilizer Application Rates (kg/ha) in 2005 for iPETS regions: CLM vs. FAO. See Fig.1 for region definitions.

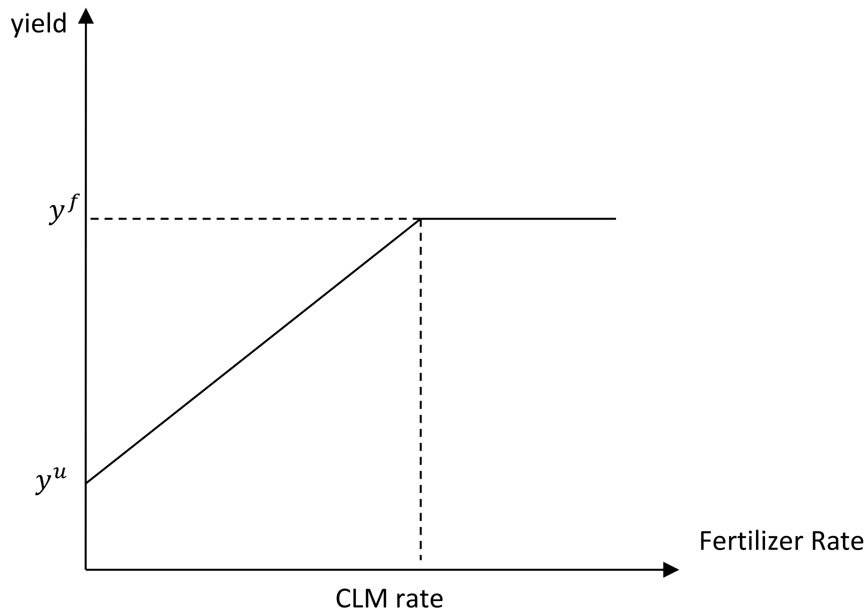
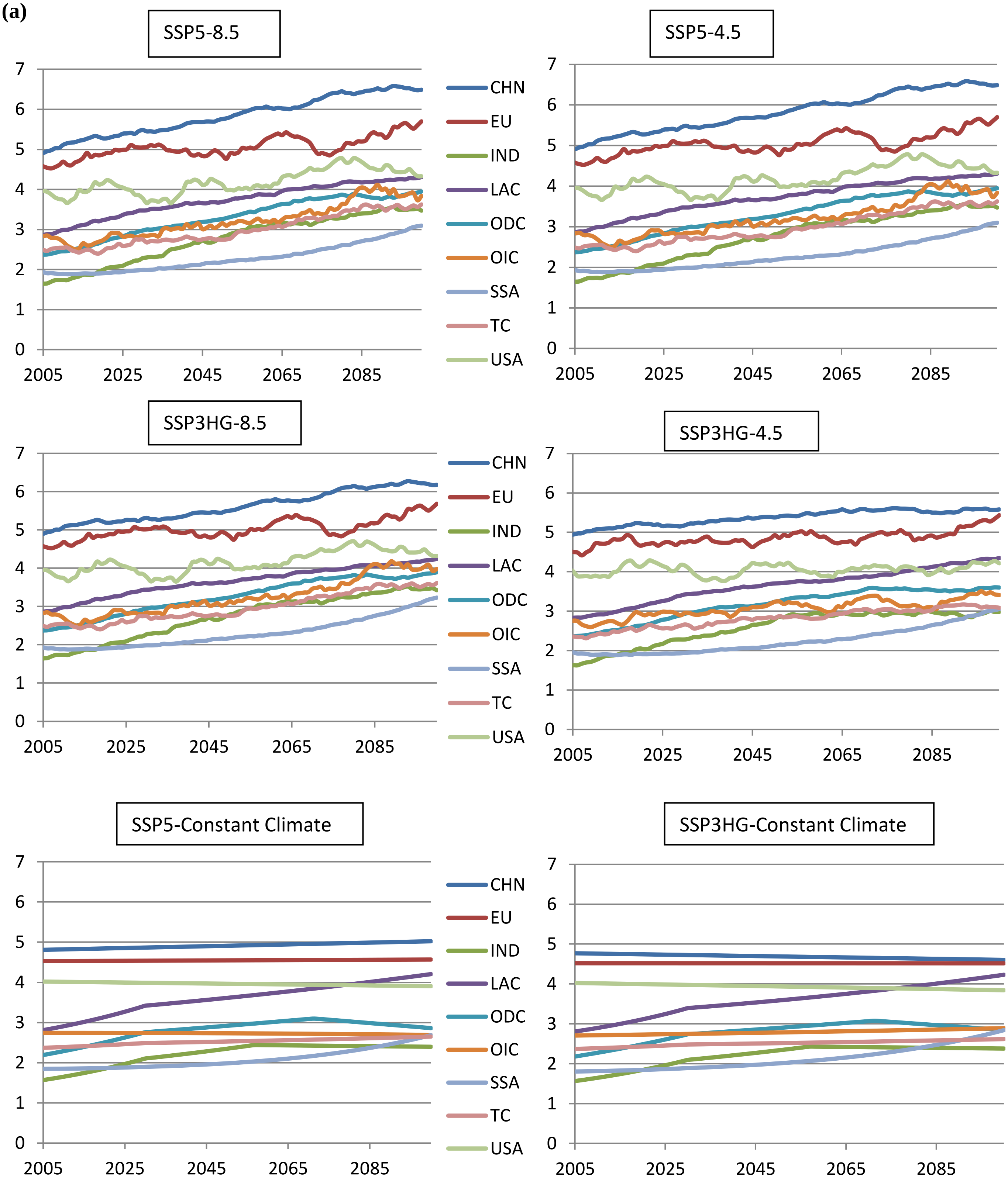


Fig.8

Curve used to decide yields with different fertilizer application rates. The unfertilized yield for region r at time t from CLM is y^u and the fertilized yield is y^f. The adjusted yield follows this curve in with the corresponding FAO fertilizer rates.

(a)


SSP5-8.5
SSP5-4.5
SSP3HG-8.5
SSP3HG-4.5
SSP5-Constant Climate
SSP3HG-Constant Climate
0
1
2
3
4
5
6
7
2005
2025
2045
2065
2085
CHN
EU
IND
LAC
ODC
OIC
SSA
TC
USA

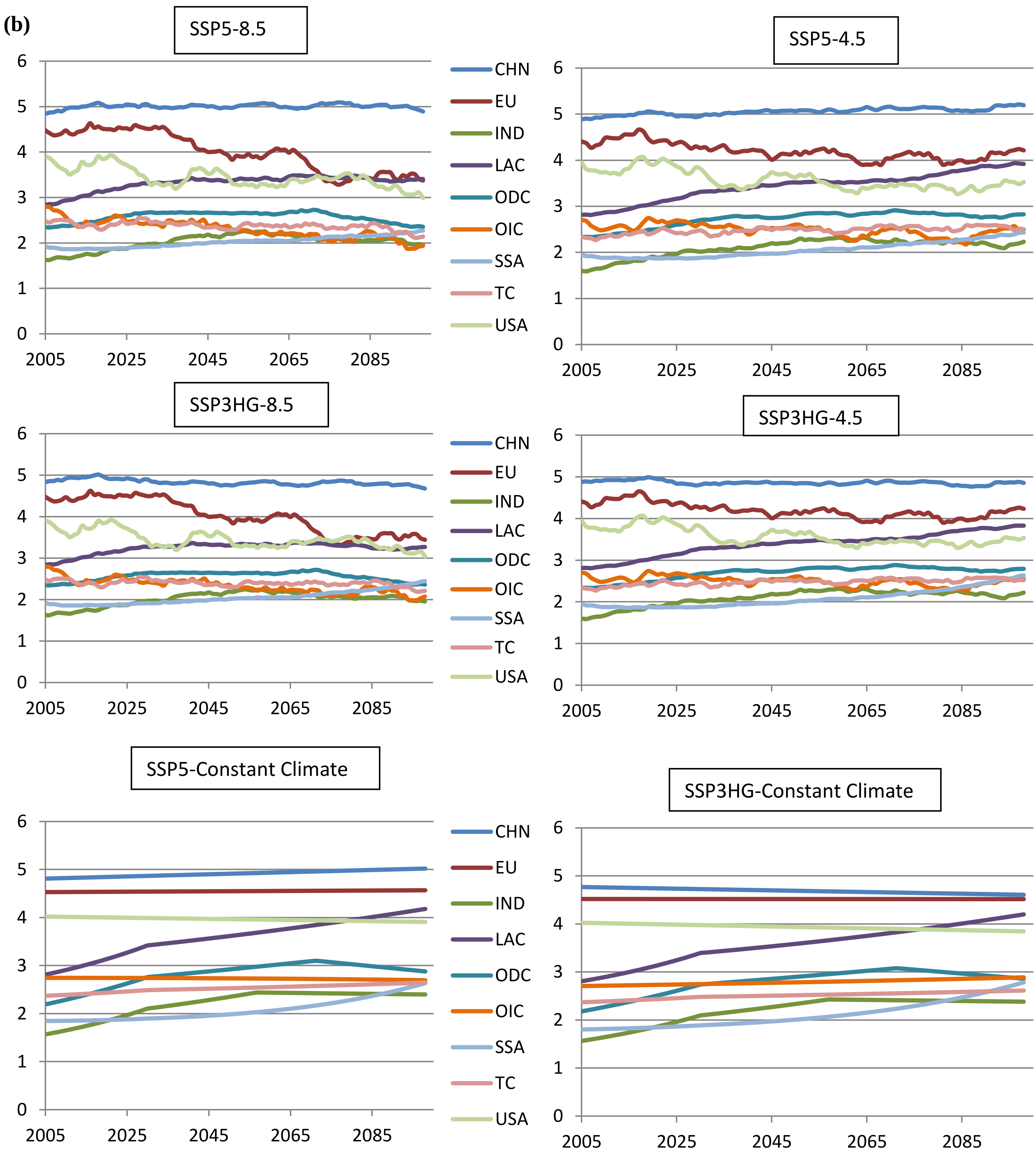


Fig.9

CLM yields aggregated into iPETS regions after adjusted for management practices and smoothing with (a) or without (b) CO2 fertilization. See Fig.1 for region definitions.

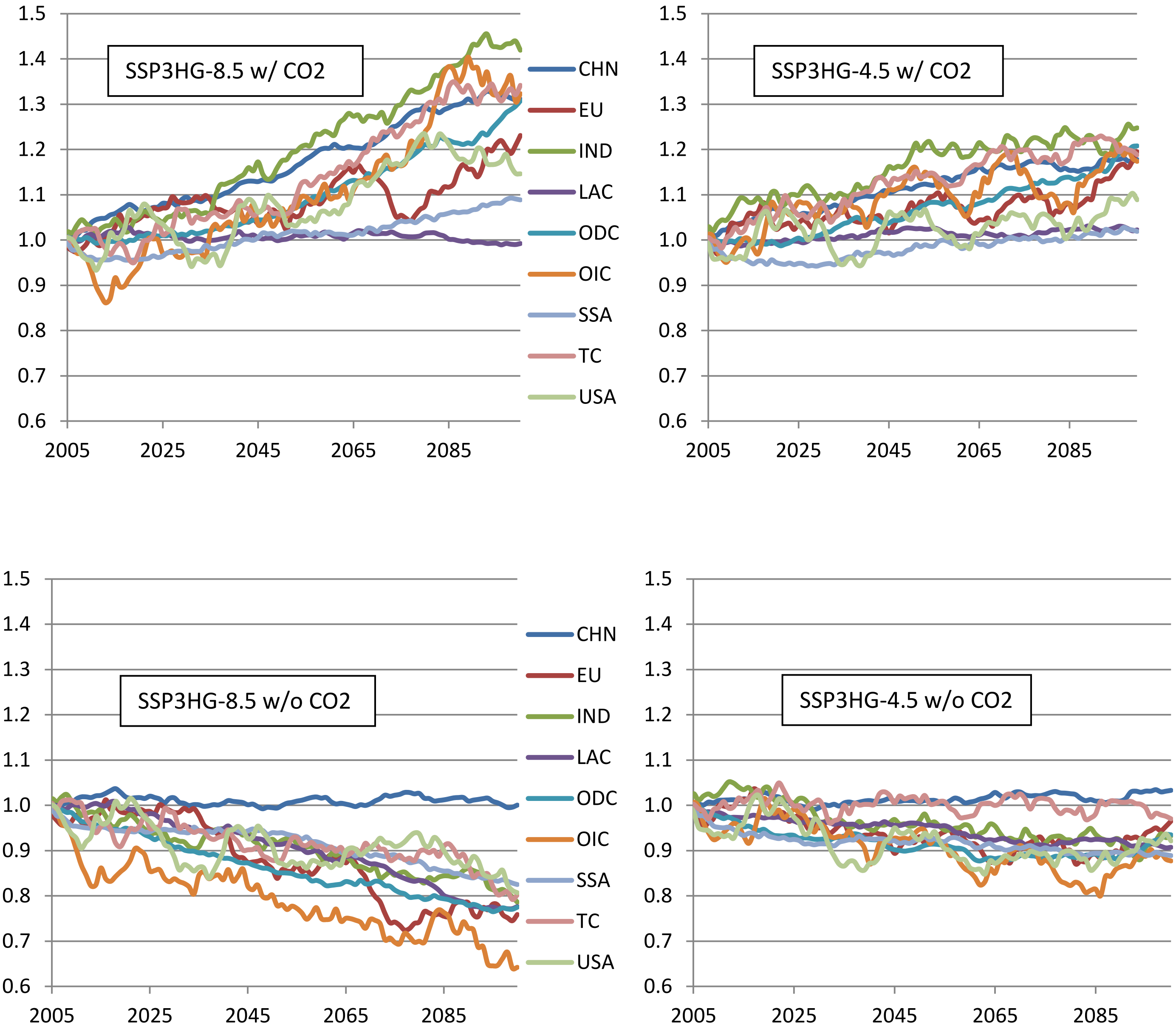


Fig.10

Aggregated Yield Changes for iPETS Regions for SSP3HG, similar to Fig.2 in main text. See Fig.1 for region definitions.

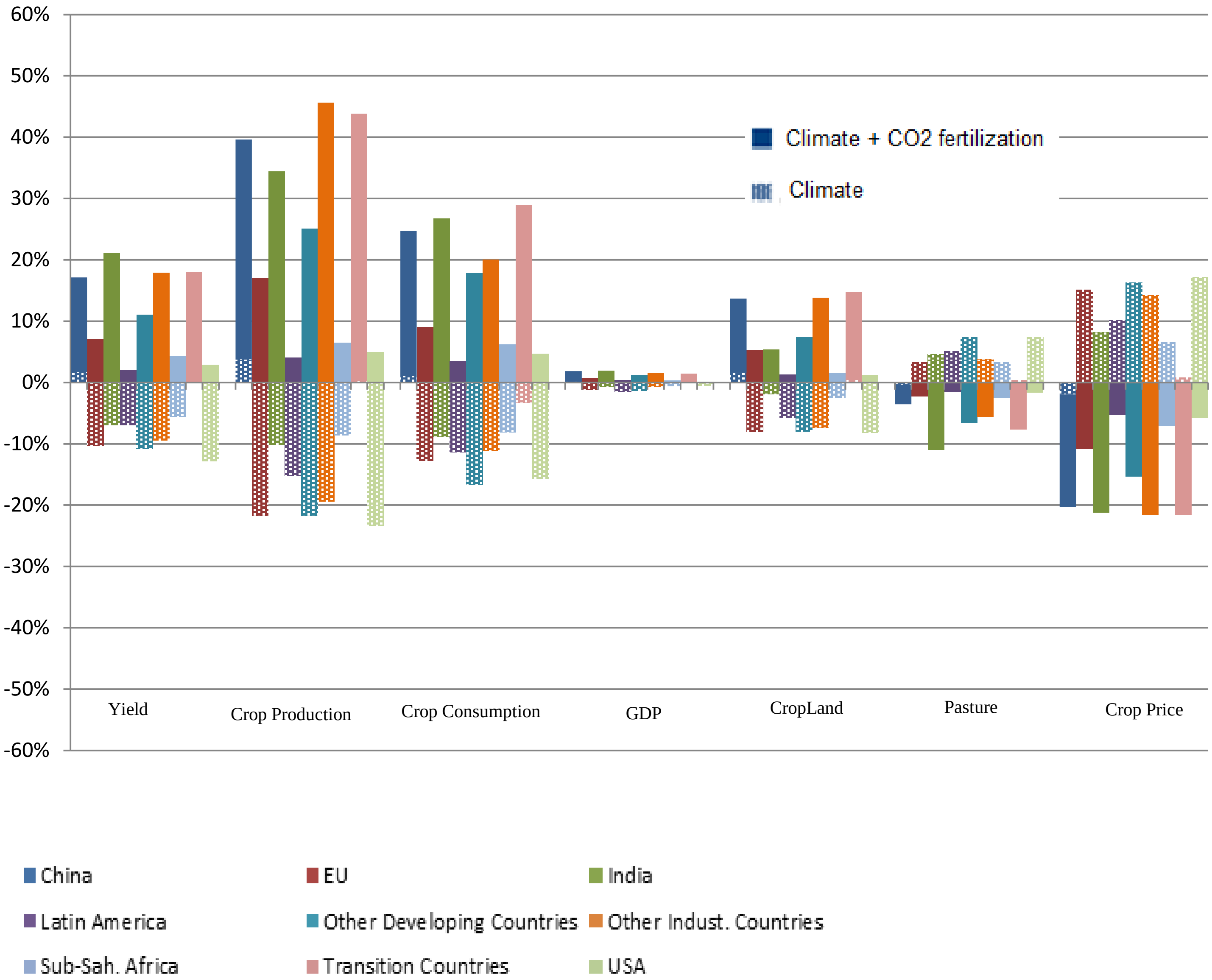


Fig.11

Climate impacts on the economy (average 2061-2080) for SSP5-4.5, expressed relative to outcomes in SSP5-4.5 scenario without climate change, similar to Fig.4 in main text.

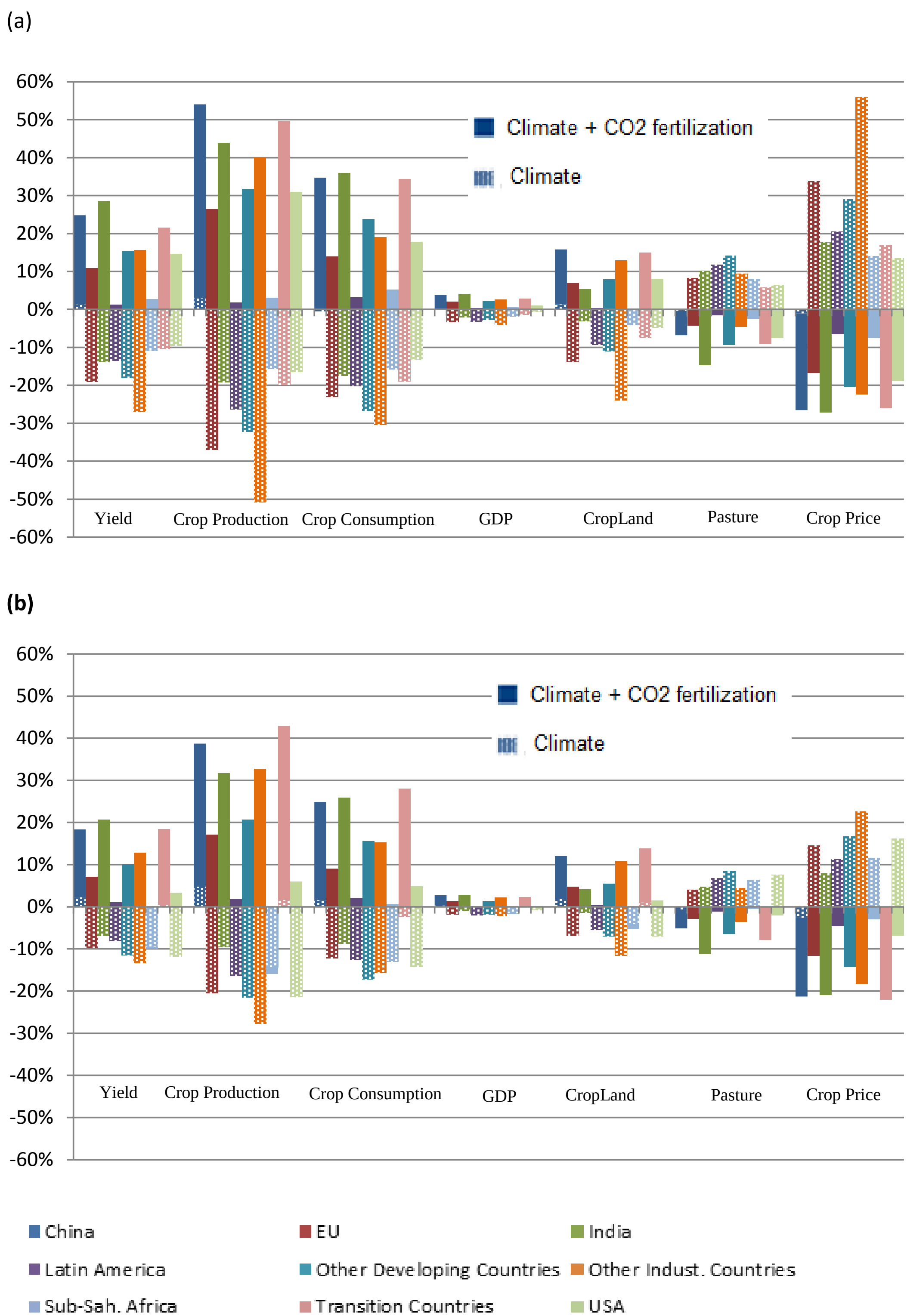


Fig.12

Climate impacts on the economy (average 2061-2080) for SSP3HG-8.5(a) and -4.5(b), similar to Fig.4 in main text.

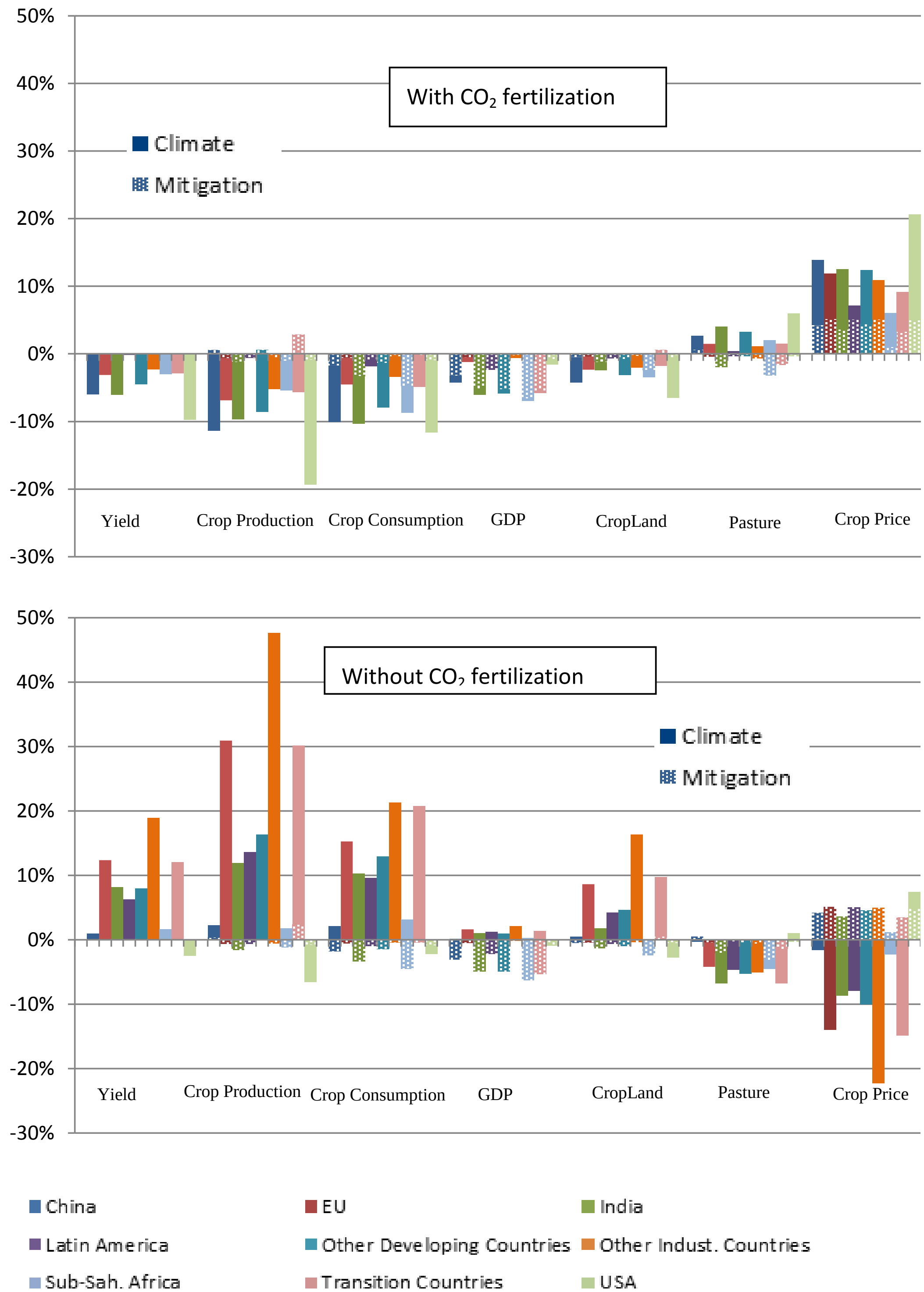


Fig.13

Avoided impacts on the economy (average 2061-2080) in SSP3HG-4.5 compared to SSP3HG-8.5, expressed relative to outcomes in SSP3HG-8.5, similar to Fig.5 in main text

Table 1. Idealized CLM Model Runs

Climate	CO_2 Fertilization	N Fertilizer	Irrigation
RCP8.5	w/	w/	Irrigated
			Rainfed
		w/o	Irrigated
			Rainfed
	w/o	w/	Irrigated
			Rainfed
		w/o	Irrigated
			Rainfed
RCP4.5	w/	w/	Irrigated
			Rainfed
		w/o	Irrigated
			Rainfed
	w/o	w/	Irrigated
			Rainfed
		w/o	Irrigated
			Rainfed
Constant Climate	w/o	w/	Irrigated
			Rainfed
		w/o	Irrigated
			Rainfed