Impact of Climate Change on Global Agricultural Markets under Different Shared Socioeconomic Pathways

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Abstract

We quantify changes in global agricultural trade by 2050 for maize, rice, soybeans, and wheat due to variations in commodity yields triggered by climate change. Our scenarios are differentiated by population levels and economic growth rates associated with three shared socioeconomic pathways. A baseline assuming no climate change is compared to a scenario consistent with a representative concentration pathway (RCP) assuming a radiative force of 8.5 W m^{-2}, i.e., RCP8.5. The baseline and the scenarios will establish an upper and lower bound of economic effects associated with yield changes from climate change. Our results show price increases for maize of 61.3%-80.9%, for soybeans of 36.7%-51.7%, and for wheat of 5.4%-11.1% depending on the shared socioeconomic pathway. Rice benefits from CO_2 fertilization and we see a relatively constant price decrease of 19.5%-19.9% across the scenarios. Global agricultural area for all scenarios is expected to be higher between 1.3% and 2.3% in 2050. Depending on the crop and country/region, there are significant reductions in production especially for maize. Absolute changes in trade patterns are most pronounced for wheat and least for rice. The increase in cropland will lead to additional carbon emissions enforcing climate change. Intra- and inter-country welfare changes are inevitable under climate change given the increases in crop prices and changes in trade. Our policy implications highlight the importance of economic growth, which leads to lower commodity prices in absolute terms and hence, higher food security. Less cropland is used under the higher economic growth scenario, which represents a trade-off given the potential for higher carbon release under higher economic growth.

Keywords: Land-use change, crop yield, international trade, representative concentration pathway

1 Introduction

The effects of climate change on global food production and food security through crop yield levels and variability are receiving increasing attention because negative impacts on major crops are expected (Müller and Robertson, 2014; Rosenzweig et al., 2014; Carraro, 2016; Iizumi et al., 2017; Zhao et al., 2017; Schauberger et al., 2017; Schleussner et al., 2018; Huffman et al., 2018; Arora et al., 2020). Investments in agricultural research and development (R&D) needed for offsetting some of these yield losses (Baldos et al., 2020), and the implications of changing levels of yields and variability of these yields for crop insurance (Tack et al., 2018) have also been estimated.

Although global average crop yields are expected to decrease, there are regional and crop-specific differences in magnitude and direction of change (Hertel et al., 2010; Müller et al., 2011; Müller and Robertson, 2014; Wiebe et al., 2015; D'Agostino and Schlenker, 2016). Previous research has modeled the effects of climate change on crop yields but fewer studies have assessed the impact on trade (Rosenzweig and Parry, 1994; Reilly et al., 1994; Parry et al., 1999; Peña-Lévano et al., 2019). The purpose of this analysis is to quantify the effects of climate change on commodity prices, land-use, production, and trade for maize, rice, soybeans, and wheat. We assess the impacts under three different socioeconomic environments with regard to economic growth and population dynamics in the presence of CO_2 fertilization, which potentially leads to higher yields with climate change under certain conditions (Iizumi et al., 2017). We combine an established agricultural outlook model with yield projections until 2050. The yield projections include socioeconomic changes and technological change (Iizumi et al., 2017; Huffman et al., 2018). Although a shorter time horizon is used in our analysis — some models go until 2100 — we see important changes in trade due to yield reductions for major agricultural producers. We shed light on the possible effects in the medium-term that climate change and its impact on yield may have on global agricultural markets.

The general approach in developing yield estimates is to combine Representative Concentration Pathways (RCP) developed for the Intergovernmental Panel on Climate Change (IPCC) with General Circulation Models (GCM) and global climate models to forecast long-term climate (van Vuuren et al., 2011, 2014; Nelson et al., 2014a). Generally speaking, RCPs present plausible future CO_2-equivalent concentration scenarios (measured in parts per million). Subsequently, crop growth models are used to translate the effects of temperature and precipitation on crop growth (Nelson et al., 2014a,b). In order to determine the effects on food production and food security, analyzing yield changes in individual countries is not sufficient because variability in production results in trade pattern changes and different prices. For example, if yields are declining, then the resulting higher prices may induce farmers to increase acreage. In addition, if the yield changes differ by location, then we are also faced with a shift in production and trade among other effects (e.g., deforestation). The purpose of this paper is to assess those effects until 2050 by combining an extended version of a global agricultural outlook model (i.e., the CARD Model[1]) with global yield projections under a scenario of no climate change and the highest RCP, i.e., RCP8.5, to obtain upper and lower bounds of the economic effects.

We contribute to the literature and policy debate of climate change and agriculture in multiple ways. First, climate change affects global agricultural productivity and not just in a single country or region. This leads to changes in imports and exports, and hence to a reallocation of (land) resources within a country (Baker et al., 2018). Because the CARD Model is global in coverage, shifts in the comparative advantage across space and time is taken into account. Second, previous literature compares current trade patterns to future patterns with climate change. We use data to simulate a future without climate change and can expand the comparison of the future with and without climate change. Merging of global yield estimates with agricultural trade models is necessary to obtain an accurate image of the price, production, and welfare changes associated with climate change. Third, the impact on food production has food security implications, particularly in developing countries. And lastly, we contribute to the policy discussion about the effects of economic and population growth on agricultural markets. Our scenarios include a low and high economic growth scenario and we show that high economic growth leads to lower food security, lower commodity prices, and lower cropland area use. Lower commodity prices under high income growth contribute to consumer welfare. Lower cropland use under high economic growth avoids carbon emissions from native vegetation but can potentially increase emissions from other

[1]The base model was developed at the Center for Rural and Agricultural Development (CARD) at Iowa State University.

industries.

2 Background on Agriculture and Climate Change

Modeling the impact of climate on yields and agriculture is usually done through (1) statistical models relating observed climate variables to yields, (2) process-based models which capture bio-physical linkages, or (3) integrated assessment models (IAM) that contain a feedback loop to socioeconomic variables such as land management (Ciscar et al., 2018). Statistical models are based on historical weather and yield variables and thus, do not capture the effects of changes in management practices due to adaptation and/or mitigation efforts or CO_2 fertilization. The advantage of these statistical models is the availability of detailed yield and weather data at the regional and global scale. Process-based crop models have the advantage of being able to model yields based on bio-physical relations such as nitrogen inputs, water availability, soil quality, and/or temperature. These models require a significant amount of input data and are therefore more difficult to implement. Müller and Robertson (2014) assess the upper bound of yield projections by using the emission scenario RCP8.5 (a radiative force of 8.5 W m^{-2}) and two GCMs (i.e., HadGEM2-ES and IPSL-CM5A-LR) in combination with two global crop growth models: Decision Support System for Agrotechnology Transfer (DSSAT) and Lund-Potsdam-Jena managed Land (LPJmL). An extensive review of process-based models is presented in the supplemental materials of Rosenzweig et al. (2014). The aforementioned methods to model climate change impacts on agriculture do not incorporate how changing yields affect economic decisions by farmers and society as a whole. To overcome this limitation, integrated assessment models were developed, which incorporate management decisions such as land-use by farmers based on climate variables and also account for how these affects change climate variables (Nelson et al., 2014a; Hertel and Lobell, 2014). For example, IAMs are able to incorporate how yield decreases triggered by climate change affect farmers' decision to increase crop area into pastures and forests and hence, release biomass carbon that subsequently extenuates carbon concentration in the atmosphere.

There is a large literature on estimating the consequences of climate change on agricultural yields at the regional and national level. Schlenker and Lobell (2010) predicts yield loss of 17%-

22% for major cereals, i.e., maize, sorghum, and millet, in Sub-Saharan Africa by 2050. Müller et al. (2011) review a large number of academic papers on the impacts of climate change on African agriculture. Across statistical, econometric, and process-based models, they find a wide range (-100% to +168%) of possible impacts of climate change on agricultural production in Africa. The authors also suggest that CO_2 fertilization could be especially useful in mitigating some of the strong negative effects of climate change on African agriculture.

Multiple authors assess the impact of climate change on U.S. agriculture in general or specific regions in particular. Multiple authors focus their analysis on the U.S. Midwest and Great Plains given the importance for corn, soybeans, alfalfa, and wheat production (Lobell et al., 2014; Lant et al., 2016; Kukal and Irmak, 2018; Crane-Droesch, 2018; Arora et al., 2020). The general consensus is that there are significant decreases in yield for maize of 30% or more and the importance of vapor pressure deficit (VPD) and soil moisture in future climate scenarios (Lobell et al., 2013). Miao et al. (2016) finds that corn and soybean production in the Eastern U.S. declines by 7%-41% and 8%-45%, respectively, in the long-run (average for 2061-2080). In the medium-run (average 2041-2060), the authors expect yield decreases for corn between 13.4% and 13.9%. This is less than the expected decrease in our analysis, which assumes corn yield decreases between 26.5% and 27.7%. Our yield decrease is more in line with Crane-Droesch (2018) who finds corn yield decreases of approximately 30% in the RCP8.5 scenario and the years 2040-2069. Arora et al. (2020) find, for the U.S. Northern Plains, yields reductions for the 2031-2055 period of 33% and 44% for soybeans and corn, respectively. These authors use the RCP4.5 scenario. For the entire U.S., Schlenker and Roberts (2009) project area-weighted yield decreases of 30%-46% and 63%-82% by 2100 under slowest and fastest warming conditions, respectively. Assuming a shift in the spatial distribution of U.S. cropping patterns, Leng and Huang (2017) find that the yield decrease is dampened compared to the situation of fixed cropping patterns, which result in a corn yield decrease of 20%-40% by 2050.

For Europe, Passel et al. (2017) find that, in terms of farmland value, the effects of climate change for European farms are slightly more pronounced than for U.S. farms. In 2100, farmland value change between -32% to 5% depending on the climate scenarios with farms in the Southern parts of Europe being affected more adversely. Although echoed for other regions, research for Europe also highlights the importance of farmers' adaptation with regard to climate change (Fezzi and Bateman, 2011; Moore and Lobell, 2014; Fezzi et al., 2015). Moore and Lobell (2014) find that maize is well suited for adaptation in Europe and negative consequences can be avoided by changes in farmers' management practice whereas barley and wheat are likely to suffer losses in terms of farmland value.

Region-specific literature as cited before can serve as the building block for global models to evaluate food availability and food security. Climate change affects every country and region differently and thus, there will be changes in trade patterns. To jointly evaluate the impacts of climate change by country and the resulting trade effects, climate and crop models must be coupled with agricultural trade models. Rosenzweig and Parry (1994) conduct one of the earliest works on agricultural trade implications and climate change using the Basic Linked System (BLS) to model agricultural trade. They assume 555 parts per million (ppm) by 2060, which corresponds to a doubling of emissions and an increase of about 4° C. Using three GCMs (i.e., Goddard Institute for Space Studies, Geophysical Fluid Dynamics Laboratory, and United Kingdom Meteorological Office) and assuming no farm-level adaptation (e.g., changes in planting date, and application of fertilizer and irrigation), they predict a reduction in global cereal production by 11%-20% compared to the baseline resulting in price changes of 24%-145%. Including farm-level adaptation results in cereal production changes from -5% to 1%. More recent analysis has highlighted the importance of farm-level adaptation because it can lead to an increase in production of 7%-15% compared to the case without farm-level adaptation under climate change (Challinor et al., 2014). The adaptation is less effective for maize than it is for rice and wheat (Challinor et al., 2014; Moore and Lobell, 2014). The yields calculated by Rosenzweig and Parry (1994) were used by Reilly et al. (1994) in the Static World Policy Simulation (SWOPSIM) agricultural trade model to calculate the welfare effects by country and also to producers and consumers within a country.

Parry et al. (1999) use the BLS to assess the effects of climate change on trade. Their extension of the analysis done by Rosenzweig and Parry (1994) assesses the rate of change in addition to the magnitude. Utilizing the same trade model used by Rosenzweig and Parry (1994), Fischer et al.

(2005) conclude that socioeconomic development is more important to food security than climate change impacts. They also highlight the importance of adjusting planting dates and cropping systems to reduce the adverse effects of climate change. Similar to Tobey et al. (1992) and Stevanović et al. (2016) among others, they find a shift in production from South to North, e.g., in Russia and North America. Tropics will not benefit from climate change due to rising temperatures but some temperate regions benefit because growing seasons are going to be longer (Rosenzweig et al., 2014). For example, rice is tolerating more heat better than wheat, which is evident in previous research as well as in our study (Baker et al., 2018; Baldos et al., 2019).

Hertel et al. (2010) use the Global Trade Analysis Project (GTAP) Model to estimate the impact on commodity prices and welfare given likely crop yield shocks (i.e., low, medium, and high productivity). Their focus is on household activity within countries because households selling surplus production in the market could benefit from climate change if commodity prices are higher. Although their analysis results in small commodity price changes under medium productivity shocks, the negative effect on food prices and household welfare under low productivity can total over 20% in countries like China, Bangladesh, Venezuela, and many countries in Africa. Deryng et al. (2014) find a mean decrease in maize yields of 2.9%-12.8% by 2080 and an increase in soybeans and spring wheat yields of 7.1%-15.3% and 9.9%-34.3%, respectively, compared to the reference year 1980. Although they show that global soybean and wheat yields improve over time, there are spatial variations, and tropical and sub-tropical regions could face substantial yield declines. There will be a general shift of climate zones (and thus agricultural productivity) northwards (IPCC, 2020). Food security is projected to decrease with climate change especially as more extreme events such as droughts result in effects across multiple regions and sectors (IPCC, 2020). Although at significant costs, research-and-development-led adaptation could contribute to a slower cropland expansion, improved food security through lower prices, and to environmental sustainability (Baldos et al., 2020).

An unintended consequence of climate change policy in the form of forest carbon sequestration (FCS) credits is demonstrated in Peña-Lévano et al. (2019) who find that an aggressive FCS policy can raise food prices significantly. This is caused by the increased competition of forests and crops for land area. This competition proves to be very detrimental if combined with decreasing yields. This finding is also echoed by van Meijl et al. (2017) who find negative impacts of carbon mitigation policies in all of their climate scenarios.

Besides the impact of climate change on trade pattern, the importance of unobstructed trade on food security and malnutrition has been the subject of previous research as well (Brown et al., 2017; Gouel and Laborde, 2018; Smith and Glauber, 2020). Baldos and Hertel (2015) use the SIMPLE (Simplified International Model of agricultural Prices, Land-use and the Environment) Model to assess the impact of trade restrictions, i.e., imperfect access to global crop markets by domestic consumers, increases the head count of malnutrition. Their results highlight two aspects: First, the presence of CO_2 fertilization can reduce the head count of malnutrition and second, integrated markets have a lower count of malnourished people than trade-restricted markets. Similar results are shown in Stevanović et al. (2016) who assess the impact of climate change across 19 GCMs and under a liberalized and so-called fixed trade scenario. The fixed trade scenario represents fixed relative shares of trade flows at the regional level. They find that unconstrained global trade reduces the adverse effects. These observations are important as many countries are implementing policies of domestic protection in an effort to alleviate short run food crises (Smith and Glauber, 2020).

3 Modeling Approach

To quantify the effects of climate change on global agricultural production, we use a well-established global agricultural outlook model, i.e., the CARD Model, whose changes for this analysis are described below. Next, we outline the adaptation of the Shared Socioeconomic Pathways (SSP) to match the countries and regions in the CARD Model. The final two section outline the climate change scenarios as well as the yield data obtained from Iizumi et al. (2017).

3.1 CARD Model

The CARD Model is a deterministic agricultural modeling system used to quantify the impact of changes in market conditions and policies on global price, land allocation, production, and trade.

The model uses a partial-equilibrium framework to solve for a set of commodity prices to equate global supply and demand for agricultural products. The model is non-spatial in the sense that trade flows are not assessed between individual countries but are aggregated. The CARD Model has been used in numerous academic publications to evaluate U.S. and international biofuel policy (Elobeid and Tokgoz, 2008; Dumortier et al., 2011; Elobeid et al., 2012; Carriquiry et al., 2019) and carbon policies (Dumortier et al., 2012).

The version of the CARD Model used in this analysis is modified compared to the previous modeling system to better capture the long-term nature of climate change. These changes include (1) an extension of the time horizon projected to 40 years as opposed to the original 10-15 years used in previous versions to better reflect the longer time horizon associated with climate change processes, (2) the incorporation of nutritional restrictions (such as appropriate limits on caloric intake) on the demand side, which become increasingly more important in the longer time horizon planned, and (3) crop coverage is restricted to corn, soybeans, rice, and wheat. The model is calibrated on 2013/14 marketing-year data for crops and 2013 calendar-year data for livestock and biofuels, and 40-year projections are generated for the period between 2014/15 and 2050/51. The model is recursively solved for 40 successive annual equilibria. Instead of the separate, commodity-specific models found in the previous version of the CARD Model, the current version of the modeling system is comprised of countries/regions with all agricultural sectors (commodities) contained within each country or region. There are 22 regional models included in the enhanced system selected according to their significance in the agricultural commodity marketplace.[2]

On the demand side, given the 40-year horizon, per capita demand for food increases with income but at a decreasing rate. That is, as consumers' per capita income increases and their food demands become increasingly satisfied, they devote smaller shares of the additional income to food products. Therefore, while there is no cap on caloric or nutritional intakes, these do not rise indefinitely as time passes and incomes increase.

[2]The countries/regions modeled are Argentina, Australia, Brazil, Canada, Chile, China, Egypt, the European Union, India, Indonesia, Japan, Malaysia, Mexico, New Zealand, Nigeria, Peru, Russia, South Africa, Ukraine, the United States, Vietnam, and the aggregate rest of the world (ROW) region required to close the model.

3.2 Shared Socioeconomic Pathways

Shared socioeconomic pathways (SSP) are future scenarios of socioeconomic development in terms of Gross Domestic Product (GDP) and population to facilitate comparability of climate change studies and models (Valin et al., 2014; Schmitz et al., 2014). The three pathways used in this analysis, i.e., SSP1, SSP2, and SSP3, can be broadly differentiated among two dimensions: (1) mitigation challenges and (2) adaptation challenges (van Vuuren et al., 2011; O'Neill et al., 2014). SSP1 has low mitigation and adaptation challenges whereas SSP3 has high challenges along both dimensions. SSP2 can be thought of as an intermediate case between SSP1 and SSP3 (O'Neill et al., 2014). The future yield evolution in Iizumi et al. (2017) are based on the nitrogen application rates, the knowledge stock of agricultural technologies, and the use of improved technologies and management systems. All of these components are influenced by the evolution of the GDP and population from the SSPs and thus, the CARD Model is run separately for each of the three SSPs in order to be consistent with the yield data used.

The SSP data provides GDP projections in real 2005 U.S. Dollars (USD) in purchasing power parity (PPP) for each country and also for aggregate regions such as the European Union (Cuaresma, 2017). All monetary values in the CARD Model are based on 2010 USD and we recalibrate the model to 2010 USD PPP using GDP data from the World Bank's World Development Indicator (WDI) database. The WDI database provides time-series PPP conversion factors for total GDP and private consumption (household final consumption expenditure).

In a first step, we deflate the GDP data in current local currency units by the GDP deflator for the year 2010 in each country to obtain the real GDP. Next, we apply the 2010 PPP conversion factor for each country to the real GDP to obtain the purchasing power parity GDP in 2010 U.S. Dollars. We then calculate the GDP growth rates associated with the SSP projections and apply these growth rates to the GDP data transformed into 2010 PPP U.S. Dollars. Thus, our GDP growth rates are consistent with the SSP scenarios. In a final step, the country data is added up to match the 22 regions in the CARD Model.

Historic population levels prior to the beginning of the simulation period calibrate the agricultural demand in the 22 regions of the CARD Model. Population data from the SSP Database is used to drive future projections (Riahi et al., 2017; KC and Lutz, 2017). Using the growth rates for the population projections instead of the level data ensures a smooth transition between the historic and projected data. We then use the same approach as for the GDP data by aggregating the SSP population data for the 22 regions and projecting the population data out based on the SSP growth rates. Hence, our scenarios are consistent with the projected SSP growth rates of population and GDP. Note that the SSP database reports the data in 5-year intervals and we interpolate between those years assuming a constant annual growth rate.

3.3 Climate Change Scenarios and Yield Data

To determine the effects of climate change on crop yields for maize, rice, soybeans, and wheat, we use the yield estimates presented in Iizumi et al. (2017). We refer the reader to the original publication for the detailed calculations and we frame our description of their approach in terms of how we use the data in our model. The calculations by Iizumi et al. (2017) cover a wide range of scenarios under various climate and socioeconomic scenarios. Their scenarios are differentiated by shared socioeconomic pathways (SSP1, SSP2, and SSP3), representative concentration pathway (RCP) (i.e., RCP2.6, RCP4.5, RCP6.0, RCP8.5), general circulation model (GCM) (i.e., GFDL-ESM2M, IPSL-CM5A-LR, MIROC-ESM-CHEM, HadGEM2-ES, and NorESM1-M), presence and absence of CO_2 fertilization, and rainfed versus irrigated crop production. The inclusion of the different SSPs at the global scale for the four crops considered also represent an extension of the Agricultural Model Intercomparison and Improvement Project (AgMIP) found in Villoria et al. (2016). Besides presenting the results for the RCPs, the authors also calculate the evolution of yields in the absence of any climate change. The yield GIS data is at a 0.5° grid size. In order to determine upper and lower bounds in terms of production, prices, and trade for our analysis, we use the no climate change data in Iizumi et al. (2017) as our baseline and use RCP8.5 as the climate change scenario. This approach of focusing on RCP8.5 is similar to Müller and Robertson (2014); Baker et al. (2018); Baldos et al. (2019). In order to use the data in the CARD Model and address our research questions, we proceed in three steps.

First, we calculate the average yield across the five GCMs, i.e., GFDL-ESM2M, IPSL-CM5A-

LR, MIROC-ESM-CHEM, HadGEM2-ES, and NorESM1-M, to obtain the ensemble mean/average, which is consistent with the approach in Iizumi et al. (2017). This is also an approach suggested by Auffhammer et al. (2013) to avoid relying on one GCM. The authors suggest reporting the range of outcomes from the different GCMs for transparency purposes (Figure 1). Since the CARD Model does not differentiate between irrigated and rain-fed crop yields, we calculate the weighted average of crop yields in a second step. To do so, we use the data by Portmann et al. (2010), which includes estimates of the annual harvested area for the four crops differentiated by rainfed and irrigated area at the global scale. Although the data is for the year 2000, the data is used by Iizumi et al. (2017) to construct the yield projections implicitly assuming that the distribution does not change over time. After aggregating the data by Portmann et al. (2010) to match the resolution by Iizumi et al. (2017), we calculate the average yield weighted by the rainfed and irrigated area for the 22 countries and regions of the CARD Model. As mentioned by Iizumi et al. (2017), "year-to-year comparison between the reported and modeled country mean yields is difficult to justify" due to the production overlapping two years. Thus, we calculate a rolling mean for each year t using the yields from $t-4, \dots, t, \dots, t+4$ to analyze decadal means, which is consistent with Iizumi et al. (2017).

Thus, for each of the three SSPs, we end up with a baseline and a scenario. The baseline assumes no climate change and corresponds to an agricultural outlook given the status quo. We also focus our calculations on the scenarios, which include CO_2 fertilization noting that the yields in the RCP8.5 scenarios are higher with CO_2 fertilization than without. Note that C_4 crops (i.e., maize) have lower responsiveness to CO_2 fertilization compared to C_3 crops (i.e., rice, soybeans, and wheat) (Hertel et al., 2010; Hertel and Lobell, 2014).

4 Results

In 2050, we see a price increase compared to the no climate change scenario for maize, soybeans, and wheat whereas a price decline is observed for rice (Figure 2). For the crops which experience a higher price, the increases are highest for the SSP1 scenario ranging from 11.1% (wheat) to 80.9% (maize) compared to the baseline with no climate change. For the SSP3 scenario, the price increases are lower and range from 5.4% (wheat) to 61.3% (maize). The increase in soybean prices ranges between 36.7% in the SSP3 scenario and 51.7% in the SSP1 scenario. Global economic growth is lowest under the SSP3 scenario, which dampens the demand for agricultural commodities. In terms of population growth, the effects on price are slightly more complicated because some major countries/regions experience highest population growth in the SSP3 scenario, e.g., Brazil, China, Indonesia, India, and the rest of the world aggregate (ROW), whereas others experience the lowest population growth in the SSP3 scenario, e.g., EU and the United States.

Across all SSPs, the decline in the price of rice is relatively consistent between 19.5% and 19.9%. Iizumi et al. (2017) whose yield data forms the basis for our analysis note that "modeled global mean relative yield for rice for years before 2000 showed some discrepancies with the reported data, causing the modeled rice yield growth to occur at a rate higher than the actual rate." The authors also mention that rice theoretically has the highest CO_2 fertilization under extreme climate, i.e., RCP8.5, but find a yield stagnation at very high concentration levels. Note that the concentration levels at which rice yield stagnates in Iizumi et al. (2017) are beyond the year 2050 and towards the year 2100.

Baker et al. (2018) find average world price responses for maize, rice, soybeans, and wheat of 26.2%, 3.1%, 30.3%, and 26.2%, respectively, across RCPs and GCMs. They note that there is significant variation in the maize prices across the scenarios ranging from -12% to over 100% under severe climate change by 2050. Their results are in line with corn prices significantly increasing under climate change and rice prices being the least affected. Our results are also consistent with Ciscar et al. (2018) who states that the effects of CO_2 fertilization have larger implications on yields than adaptation.

The evolution of commodity prices over the projection period also shows that, under no climate change, the prices for maize and soybeans stabilize close to historic levels in the SSP1 and SSP2 scenarios (Figure 3). Consistent with the population increase in populous countries in the SSP3 scenario, prices for all commodities increase. Note that the price for rice in SSP1 peaks shortly after 2040 and decreases thereafter.

From an environmental perspective, one important aspect of future food production is land-use. Although our model does not include a feedback effect of carbon emissions due to land clearing because of potentially lower commodity yields, our model quantifies land-use change. In the absence of climate change, total global area of maize, rice, soybeans, and wheat will be 5.0%, 7.5%, and 10.3% higher in 2050 compared to 2015 under SSP1, SSP2, and SSP3, respectively. As depicted in Figure 3, the maximum amount of land used for the four commodities in the absence of climate change occurs before 2050. For SSP1, SSP2, and SSP3, the maximum extension occurs in 2035 (6.8% above 2015), 2039 (8.1%), and 2049 (10.3%), respectively depending on the interactions between economic and population growth as well as yield dynamics. The increase in area compared to 2015 under RCP8.5 is 7.7%, 9.5%, and 11.7% for SSP1, SSP2, and SSP3, respectively.

Figure 4 presents the absolute change in area harvested for the modeled countries.[3] Global agricultural area for all scenarios is expected to be higher between 1.3% and 2.3% in 2050. For some large agricultural producers such as Brazil, Canada, China, and India, there are large variations in area used across the scenarios. Total crop area in Brazil increases by 0.7 and 0.3 million hectares in the SSP1 and SSP2 scenario, respectively, but decreases by 0.3 million hectares in the SSP3 scenario. Only India, Indonesia, and Vietnam see a reduction in total crop area in 2050. Note that all three countries are large rice producers and the increase in rice yields with CO_2 fertilization are a contributing factor. The decline of yields in the U.S. for maize, rice, and soybeans does not translate into a large variation in area harvested. The combined effect of lower yields and a shift in cropland allocation results in changes in production (Figure 5). Especially for SSP3, there are significant changes for corn in the rest of the world, for rice in Brazil and China, and wheat in Russia and the Ukraine.

Comparing the no climate change scenario to the RCP8.5 scenario in 2050 reveals changes in the comparative advantage and trade between countries. Canada and the EU switch from being importing countries for maize to exporting countries under the RCP8.5 scenario for SSP1 and SSP2. The EU also changes to an exporting nation for corn under SSP3. Although the production of rice increases globally due to beneficial yield effects, the rest of the world changes from being an importing region to an exporting region only in SSP1. This also represents the shared socioeconomic pathway with the lowest population growth. Under the higher population growth rates in SSP2 and

[3] Although modeled individually, the following countries were added to the group ROW: Chile, Egypt, Japan, Malaysia, Nigeria, New Zealand, and Peru.

SSP3, the rest of the world remains an importer of rice. Under the SSP2 and SSP3 scenario, the U.S. switches from a corn exporter to an importer although barely in the SSP3 scenario. This is the result of significant yield decline in the U.S. by 2050 and almost no change in area. For soybeans, no country changes its net export situation, i.e., no switch from exporter to importer or vice versa occurs. For wheat, we observe that India switches from an exporting nation to an importer in SSP1 and SSP2. India's wheat exports are minimal in the no climate change scenario and the increase in population results in wheat imports in the climate change scenario.

Large increases in maize export quantities are observed for Argentina (11.7%-24.4%) and the Ukraine (32.8%-43.2%). Brazilian corn exports decrease between 89.3% (SSP3) and 98.3% (SSP1) in the RCP8.5 scenario whereas its soybean exports increase between 3.2% (SSP3) and 17.1% (SSP1). Rice exports of Vietnam increase between 43.9% and 45.7% across the SSPs. A relatively constant decrease around 35% in soybean exports across all SSPs is experienced by the United States. Chinese imports of soybeans are lower in the RCP8.5 scenarios. Wheat trade presents interesting results because large wheat-producing countries and regions such as Canada, China, the EU, Russia, and the Ukraine see an increase in wheat yields (Figure 1). This results in a strengthening of their export position. For the five countries/regions, the lowest and highest increase in exports is observed in the SSP3 and SSP1 scenarios, respectively. Canada increases exports by 38.5%-44.4%, China by 21.4%-26.4%, EU 46.5%-108.0%, Russia by 24.3%-36.6%, and the Ukraine by 25.1%-48.2%.

4.1 Self-Sufficiency Ratio

One important measure that policy makers may be interested in at the global level is the so-called food self-sufficiency ratio (SSR). The SSR measures the ability of a country's agricultural production to produce food for its population. To make different crops comparable to each other, the SSR is often measured on a caloric basis. The SSR is calculated as $SSR = Production \times 100/(Production + Imports - Exports)$ (Clapp, 2017). An SSR of 100 indicates that a country produces the same amount of food that they consume. A value above (below) 100 indicates that the country produces more (less) food than it consumes. We use a calorie content (in kilojoule per 100 grams) for maize, rice, soybeans, and wheat of 1527, 1506 , 614, and 1368, respectively.[4] Note that the SSR definition is such that globally self-sufficiency is attained in any type of scenario. This is also the reason why we see little change for the rest of the world (Figure 6). Some countries do benefit from climate change through increased yields such as Argentina, Canada, the EU, and Ukraine. The U.S. faces a slight decrease in its SSR. India sees a switch from a situation where the SSR is above 100 in the baseline without climate change to below 100 in the RCP8.5 scenario for all SSPs. The reverse is true for South Africa. Population size must be taken into account when interpreting the results. For example, Brazil, India, and the U.S. see a decrease in their SSR, which is significant given the population size of the country. This is not comparable to countries such as Chile, New Zealand, and South Africa — which have a relatively small population — that see an increase. Intracountry adaptation by farmers will lessen the effects of climate change and the CARD Model only accounts for changes at the national level (Baldos et al. (2019)).

5 Policy Implications

Evaluating the consequences of climate change is a highly complex undertaking and we are presenting results for the agricultural sector. Policies can aim at avoiding further long-term increases of carbon in the atmosphere (mitigation) or aim at dampening the effects of climate change on producers and consumers (adaptation). In this paper, we focus on agricultural production under climate change and in the context of three socioeconomic environments and we are going to frame our policy discussion mostly in the context of economic growth and population.

SSP1 exhibits the highest GDP growth for all countries considered in our analysis. With regard to population growth, SSP1 also exhibits the highest growth for developed countries/regions such as Australia, Canada, the EU, Japan, New Zealand, South Africa and the United States. For all other countries, it is SSP3 that results in the highest population. For SSP1, focusing on economic growth seems to result in a higher increase commodity prices given the information in Figure 2 but a closer examination of the price level reveals that prices are lower in SSP1 in absolute terms

[4]The data is obtained from https://fdc.nal.usda.gov/ for corn grain (yellow), rice (white, medium-grain, raw, unenriched), soybeans (green, raw), and wheat (hard red winter).

(Figure 3). Combined with higher overall income, this suggests poverty alleviation and improved food security for vulnerable populations. From an environmental perspective, the cost to focus on higher economic growth is a higher percentage increase in land area (Figure 4). Our results also suggest that changes in trade are least pronounced in the SPP3 scenario. This is consistent with the higher Self-Sufficiency ratio for food in SSP3 (Figure 6). Policy makers — besides focusing on mitigation and adaptation — can focus on economic growth to increase food security at the cost of more cropland use. Cropland use is lowest in SSP1 and reduced expansion into native vegetation can potentially decrease carbon emissions and thus, mitigate climate change. There are trade-offs from a policy perspective because higher economic growth can also lead to additional carbon emissions accelerating climate change. Under high economic growth, other detrimental environmental consequences from agriculture could emerge such as increased fertilizer use (and resulting nitrous oxide emissions) and irrigation use which has negative effects on water quality and quantity.

From a producers' perspective, there will be "winners" and "losers" depending on the location within and across countries with distributional consequences. This will bring attention to current and future policies. For example, the availability of crop insurance in the United States currently protects farmers from adverse weather and pest events. The expected decline in U.S. maize yields due to extreme climate change may call into question the feasibility and affordability of crop insurance (Tack et al., 2018). At the same time, a shift in cropping patterns to different regions, which become more suitable and more productive for crop production, may require long-term planning to dampen the effects of structural change. In this line, planning for the development or the redirecting of infrastructure and logistical channels for changing trading patterns may be needed.

6 Conclusion

There is a large body of literature on the adverse impacts of climate change on yields whereas models quantifying those effects on agricultural trade and commodity prices are limited. In this paper, we differentiate our scenarios by shared socioeconomic pathways using previously published yield data to determine the effect on prices, land-use, production, and trade under a baseline without climate change and the scenario using the highest representative concentration pathway in terms of warming. Our results show that there can be significant variations in terms of land-use, trade, and production in 2050 depending on the macroeconomic environment. Rice production benefits in the extreme climate change scenarios presented in this analysis whereas all other commodities see a decline in production. Price changes are most pronounced for maize and soybeans and least for rice and wheat. Total area for all crops increases in every scenario. The largest increase in land-use occurs in the SSP1 scenario characterized by high GDP and low population growth, which suggests that GDP plays a larger role in future agricultural production than population growth. We also evaluate the food self-sufficiency ratio for our scenario that indicates whether a country or region can fulfil all its caloric needs by its own agriculture. Noting that the ratio is constructed such that the entire world is self sufficient, there are some countries such as Argentina, Canada, and the Ukraine that significantly increase their self-sufficiency ratio because of higher yields. Thus, more agricultural production occurs in those countries under climate change.

There are several aspects that are not explicitly addressed in this paper. First, the increase in area harvested due to globally lower yield may result in the conversion of native vegetation such as grassland and forests to cropland. The resulting carbon release will exacerbate climate change leading to a different emission pathway. Second, the reduction in yields will result in increased irrigation water and fertilizer use with likely detrimental consequences on environmental quality. Changes in water usage also have policy implications on water use and property rights. These water usage changes and their location call for the integration of water models into climate change assessments. Third, commodity price increases negatively affect the welfare of consumers depending on the geographic distribution of yield changes and the macroeconomic environment. And last, this paper does not evaluate the impacts of trade restrictions on food security. Previous research has argued that the absence of trade restrictions results in a unobstructed shift of the comparative advantage to regions that benefit from higher temperatures. The hypothesized consequences are dampened effects on commodity prices and adverse welfare changes. This study analyzes four crops, which cover a significant caloric intake of global food and feed demand, but it does not include all crops and fisheries encompassing total caloric consumption. Currently, the availability of global data including more crops besides the ones covered in this analysis — and covering the SSPs and technological change as in this model — is limited (although there is significant progress of the Agricultural Model Intercomparison and Improvement Project (AgMIP)). Previous research points out that intracountry adaptation by farmers will lessen the effects of climate change. However,the CARD Model only accounts for changes at the national level. The CARD Model was developed to assess trade and production from a partial equilibrium perspective and is not set up as an integrated assessment model (IAM). Hence, we cannot iteratively take into account GHG emissions from farmers' decision and their effects on climate change.

As highlighted throughout the paper, using trade as a means to dampen the negative welfare effects of climate change will be important. Future research is needed to better understand the role of CO_2-fertilization on yields and to integrate the feedback mechanism from increased land-use and carbon emissions resulting in higher global temperatures on yields and farmers' decision making. As pointed out in previous literature, the possibility of forest carbon credits as an additional revenue source for land owners has the potential to create the unintended consequence of increasing commodity prices further. Thus, a careful assessment is necessary to meet food security and climate goals.

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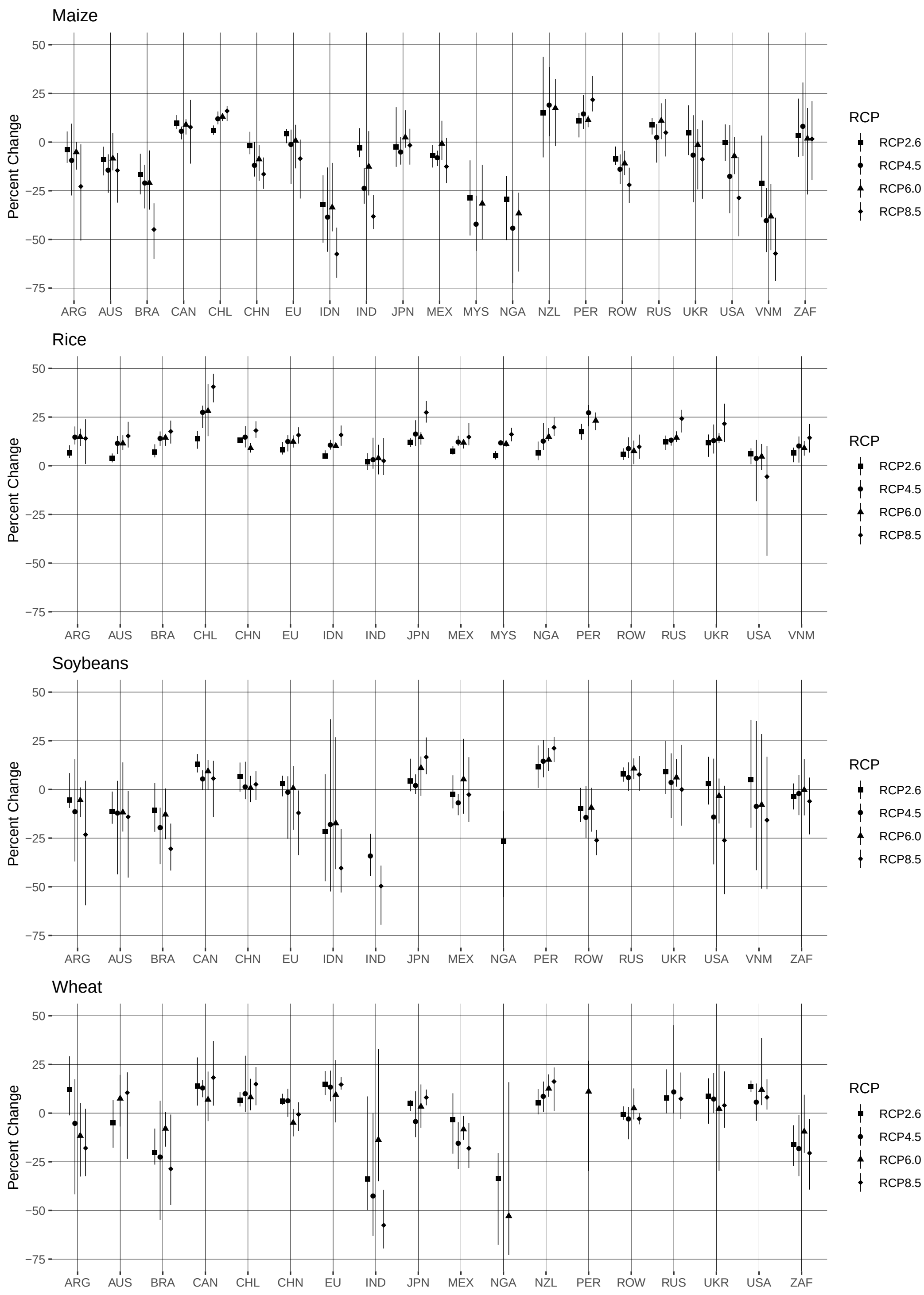

Figure 1. Minimum and maximum yield change in 2050 across the five GCMs.

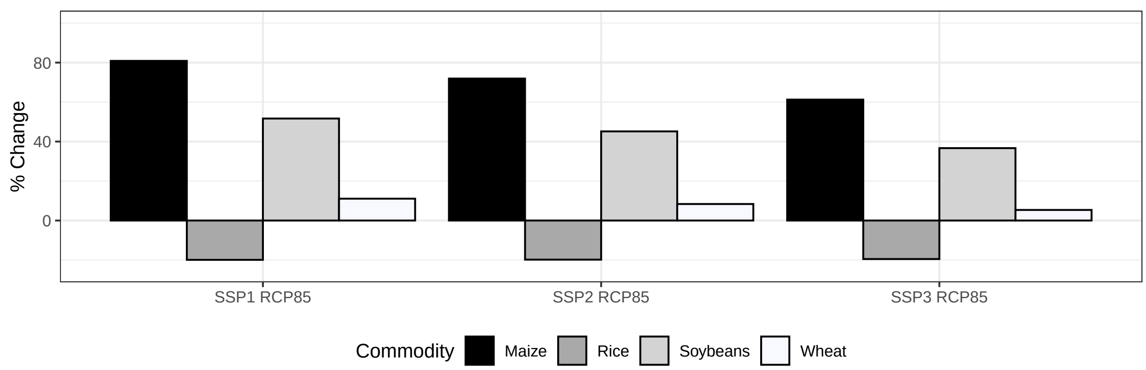

Figure 2. Changes in price compared to the no climate change scenario in 2050.

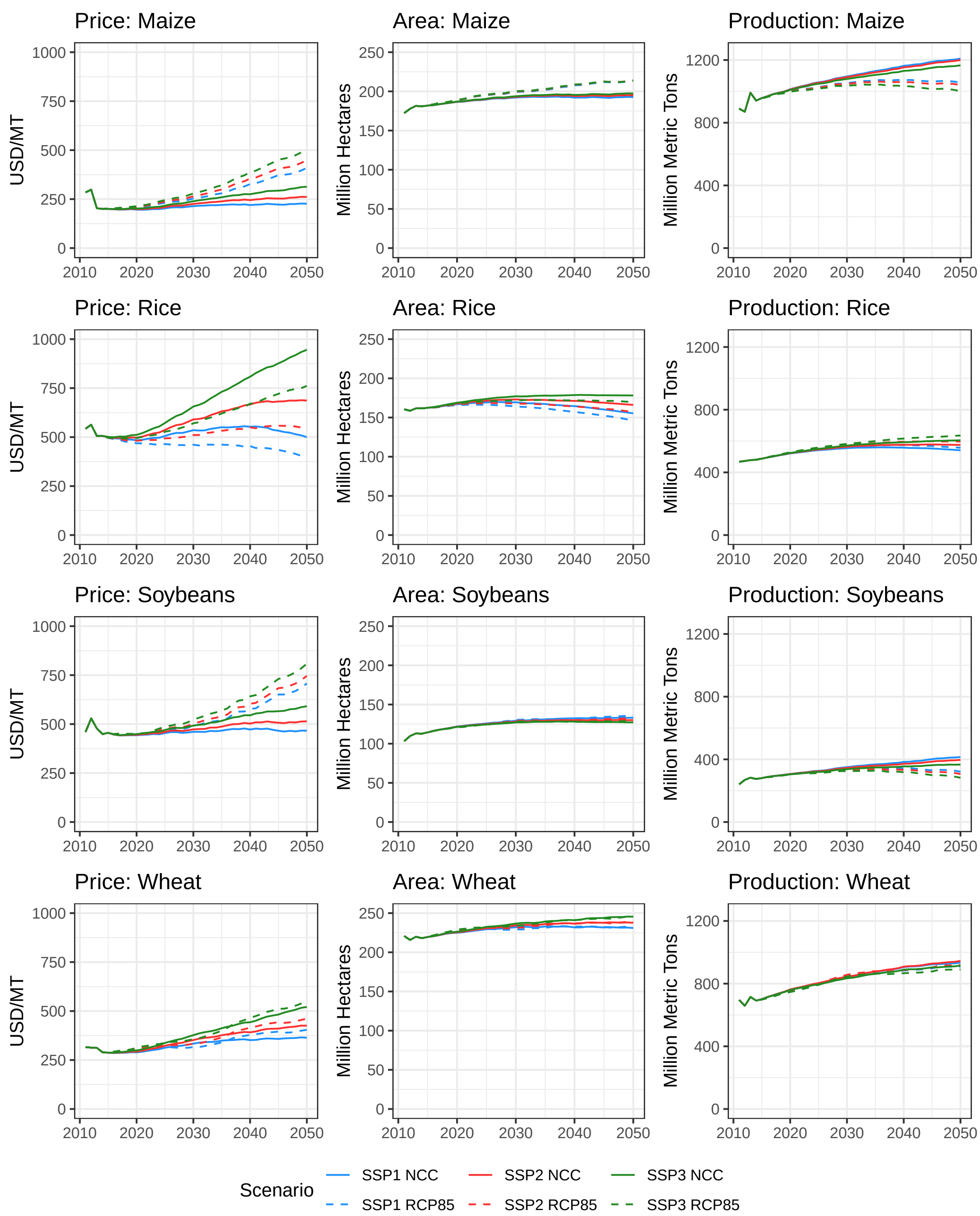

Figure 3. Price, area, and production for the Shared Socioeconomic Pathway scenarios.

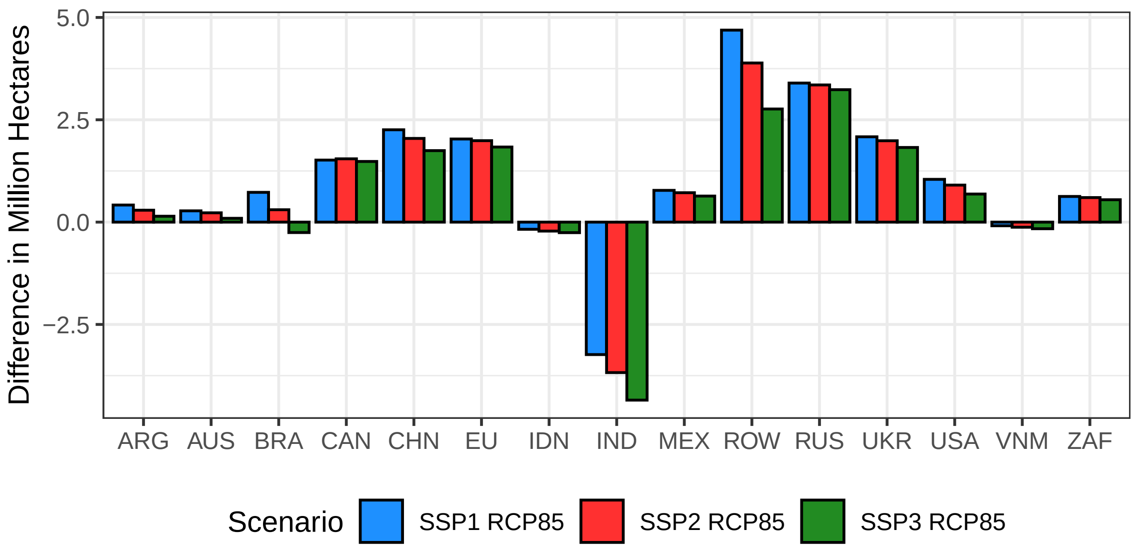

Figure 4. Difference in total area harvest in 2050 compared to the scenarios without climate change.

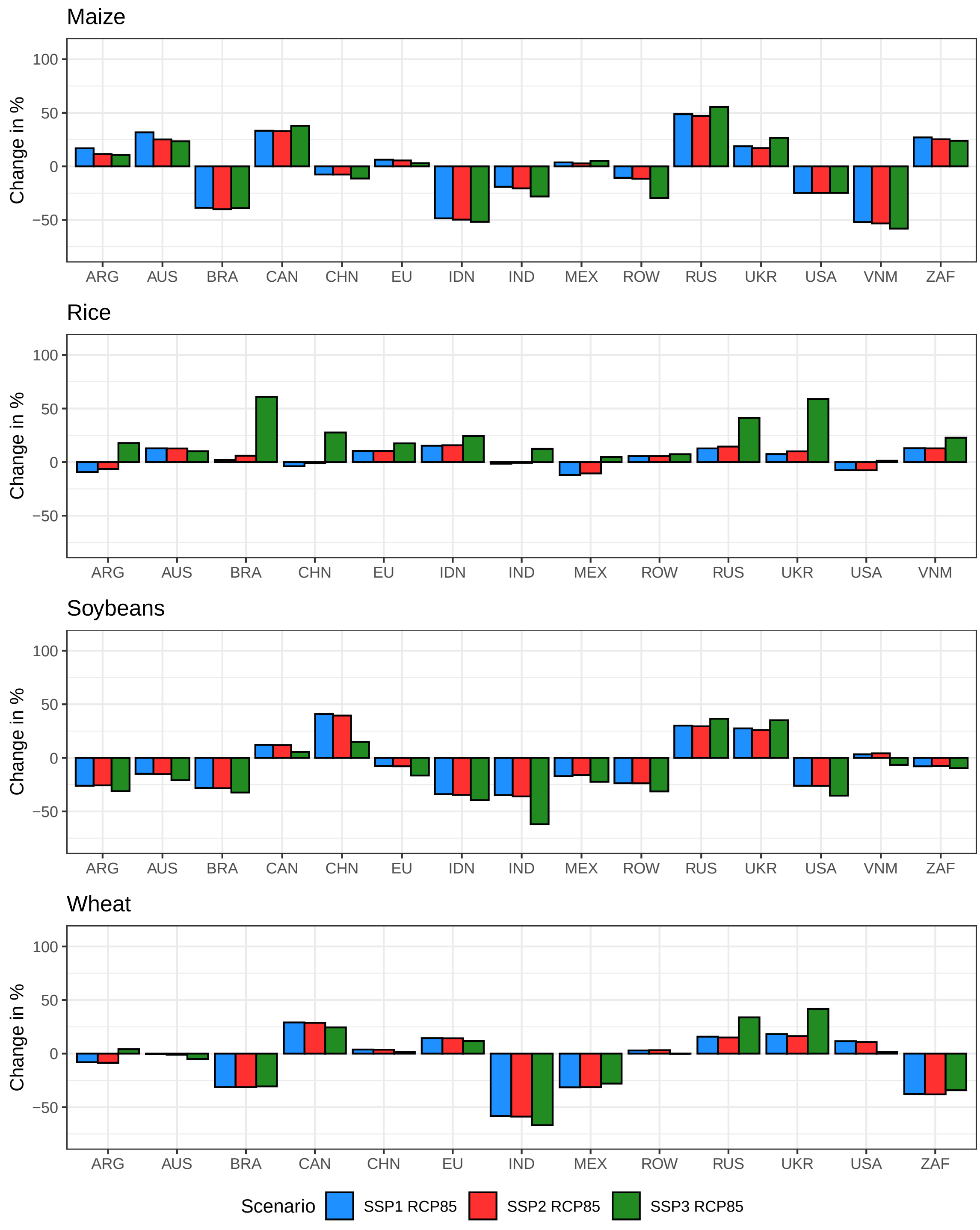

Figure 5. Changes in Production

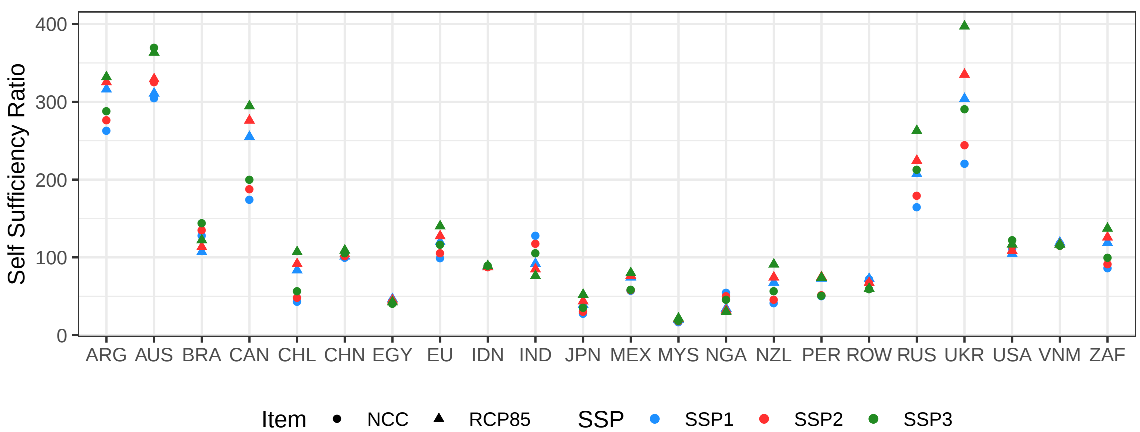

Figure 6. Changes in the Self Sufficiency Ratio between the baseline with no climate change and the RCP8.5 scenario.