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Climate change impacts on China's agriculture: The responses from market and trade

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ABSTRACT

China's food security has been facing several challenges, which are likely to be worsened due to climate change. The purpose of this paper is to provide an evidence on the impacts of climate change on China's agriculture, with particular attention to the market and trade responses. Using projected crop yield changes for China and its' main trading partners under changing climate, we employ an agricultural partial equilibrium model (CAPSiM) and a linked national and global equilibrium model (CAPSiM-GTAP) to assess the impacts on food production, price, trade and self-sufficiency of China. Our results show that climate change will have significant effects on crop production though with large differences among crops. Under the worst climate change scenario RCP 8.5, wheat yield in China is projected to decline by 9.4% by 2050, which is the biggest yield reduction among the crops. However, the market can also respond to the climate change, as farmers can change inputs in response to reduced yields and rising prices. As a result, production losses for most crops are dampened. For example, wheat production loss under RCP8.5 reduces to only 4.3% due to market response. The adverse impacts on crop production will be further reduced after accounting for the trade response as farmers adjust production to much higher prices in the more severely affected countries. The paper concludes that we need to learn more from farmers who optimize their production decisions in response to the market and trade signals during climate change. A major policy implication is that policymakers need to mainstream the market and trade responses into national plans for climate adaptation.

1. Introduction

China's agriculture is expected to face challenges in the future mainly due to rising food demand and constraints of land and water resources. Although China has largely ensured its food security in the past 40 years, it has increasingly relied on international markets to ensure its food supply since 2004 (Ali, Huang, Wang, & Xie, 2017; FAO, 2017). With increasing population, higher income and constraints of resources, the pressure on China's food security is going to increase in the future. Huang, Wei, Cui, and Xie (2017) predicted that China's overall food self-sufficiency is likely to fall from 94.5% in 2015 to around 91% by 2025.

Climate change will likely aggravate the challenges China faces on its food security in the future. China's annual average temperature has been rising significantly over the past six decades and the warming trend will continue under the future projections (Cui,

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Xie, & Liu, 2018; Liang & Yan, 2016; Meehl, 2007; Nakicenovic et al., 2000). It is generally accepted that the mechanism of climate change affecting China's agriculture is mainly through rising temperature and increasing fluctuation in precipitation (Wu et al., 2014; Edition Committee of China's National Assessment Report on Climate Change, 2015).

The impacts of climate change on China's agriculture have been widely studied in the literature through biophysical models (e. g., Li & Geng, 2013; Wang, Huang, & Yang, 2014; Xiong, Matthews, Holman, Lin, & Xu, 2007; Tao, Hayashi, Zhang, Sakamoto, & Yokozawa, 2008; Xiong et al., 2009; Piao et al., 2010). For example, Lin et al. (2005) found that the negative impacts of climate change on wheat yield in China could reach up to 5.6–18.5% under A2 scenario[1] by 2020s. Similarly, Tao et al. (2008) suggested that if the temperature increases by 1 °C, rice yield would decline by 6.1–18.6% even after considering the adaptation measures. Xiong, Conway, Lin, and Holman (2009) predicted a moderate decrease in rice yield in the range of 4.9–8.6% in 2050s. Meanwhile, some other studies also provide the evidence on positive impacts of climate change on some of the crops. Lin et al. (2005), for example, concluded that irrigated maize yield would increase slightly by 2020 under B2 scenario[1].

A major limitation of the biophysical models for assessing climate change impact is that they tend to overestimate adverse impacts of climate change on agriculture, as they fail to account for the underlying buffering capability of economic system, which the later attains through adjustments in production inputs and structure. For example, Wang, Huang, and Yang (2009) used a general equilibrium economic model to assess the climate change impacts on agriculture in China and found that the percentage decrease in production of rice, wheat, and maize in 2030 would be lower than the yield changes predicted by biophysical crop modelers. Using the global general equilibrium model (AGLINK), Zhai, Lin, and Byambadorj (2009) also found that climate change would cause China's total crop production to decrease only slightly (0.2–0.5%) in 2080. Some global studies on climate change do explicitly cover China while accounting for endogenous response of markets (Calzadilla et al., 2013; Nelson, Valin, et al., 2014; Parry, Rosenzweig, Iglesias, Livermore, & Fischer, 2004; Zhai et al., 2009; Zhou et al., 2017). Nevertheless, these studies either lack empirically based data on yield shocks for main crops in China or do not apply the detailed national economic model for China that can reflect China's agriculture market accurately.

International trade is also another important factor affecting China's food market but few studies have considered the role of trade while assessing climate change impacts on China. Around 2004, China turned a net importer of agriculture products form previously a net exporter, so much so that in 2016 > 80 million tons (Mt) of soybean was imported. At the same time, China became the world's largest importer of rice (Huang et al., 2017). There are several important global studies on the role of international trade in climate change on agriculture. For example, Reilly and Hohmann (1993) made the first attempt to discuss the role of international trade in assessing climate change impacts. Later, Baldos and Hertel (2015) explored the potential for a more freely functioning global trading system to maintain improved food security in the long run (i.e. by 2050). More recently, Brown et al. (2017) suggested that global trade would continue to play a central role in assuring that global food system adapts to a changing climate in that it is likely to facilitate the movement of food from areas of surplus to areas of deficit. However, there is no China-focused study that assesses climate change impacts on China's agriculture while accounting for the role of international trade.

The overall purpose of this paper is to provide an updated and more reliable evidence on the impacts of climate change on China's production, prices, trade and self-sufficiency of major crops, with particular focus on the market and trade responses. Our study aims to give some perspective to the studies that (i) focus only on the impacts of climate change on national food markets (ii) use single region model and (iii) fail to consider the price transmission from the rest of world. Our study examines the climate change impacts on major crops towards 2050 under the worst climate change scenario (measured with representative concentration pathway, i.e., RCP 8.5) and the best climate change scenario RCP2.6.[2] To achieve this purpose, we use the econometrically estimated projected changes in the yields of major crops in China, while we derive the projected crop yield changes for China's main trading partners from a process-based biophysical method. Next, we employ a widely-used agricultural partial equilibrium model (China Agriculture Policy Simulation Model, CAPSiM) of China to assess the climate change impacts on agriculture, thus considering the domestic market responses. Then we use the linked national and global equilibrium model (CAPSiM-GTAP) to assess the climate change impacts on agriculture, wherein we consider both the market and trade responses. The linked model approach effectively transmits the effects of foreign countries' climate shocks on agriculture to China via trade, while allowing us to use a more precise and detailed national economic model.

Our results show that the effects of climate change on crop production are significant but have large variations among crops. Under the worst climate change scenario i.e., RCP 8.5, among all crops in China, wheat yield is projected to experience the largest decrease of 9.4% by 2050. After taking into account the market response, production losses for most crop are dampened (e.g. wheat production loss reduces to only 4.3%) because of the growers' response to changes in agricultural prices under climate change. Moreover, if we consider the impacts of climate change from the rest of the world, which affect China's trade and therefore domestic production, the severity of climate change impacts on China's agricultural production will be further reduced, e.g. to around 4% for wheat. The study concludes that we need to learn more from farmers who respond to changing climate according to the market and trade signals, and further mainstream these lessons into national adaptation development plan.

The rest of the paper is organized as follows: Section 2 introduces data sources for yield changes under different climate change

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[1] A2 and B2 scenarios represent different carbon emission pathways and correspondingly different temperature increase in the future.

[2] RCP2.6 and RCP8.5 are named after a possible range of radiative forcing values in the year 2100 relative to pre-industrial values (+2.6 and + 8.5 W/m^2, respectively). We can easily see that RCP2.6 and RCP8.5 represent low and high carbon emission pathways and correspondingly low and high temperature increase, respectively, in the future (IPCC, 2014).

Table 1
The crop production (Mt) and climate change impacts on crop yield of China under RCP 2.6 and RCP 8.5 (%).

	Production (2012)	2030		2050	
		RCP2.6	RCP8.5	RCP2.6	RCP8.5
Wheat	121.02	−2.28	−3.39	−4.83	−9.39
Rice	204.24	−0.56	−0.78	−1.34	−2.60
Maize	205.61	0.33	−0.01	0.25	0.31
Soybean	13.60	0.26	0.08	0.31	0.42
Cotton	6.84	0.73	1.76	1.74	4.24
Rapeseed	14.00	−0.17	0.18	0.03	0.61
Peanut	16.69	−0.20	−0.20	−0.37	−0.20
Sugar beet	11.74	−0.35	−0.14	−0.65	−0.38

Note: The base year is 2012.
Source: The production in 2012 comes from the CAPSiM database; the yield change comes from Wang, 2016.

scenarios for China and its main trade partners. Section 3 describes the simulation methodology, baseline scenario and climate change scenarios. Section 4 presents and analyzes the results for climate change impacts on China's agriculture and the role of market and trade. Section 5 concludes the study with policy implications.

2. Climate change shocks for biophysical yields of crops in China and the rest of world

2.1. Climate change shocks for biophysical yields of crops in China

In this study we cover rice, wheat, maize, soybean, cotton, rapeseed, peanut and sugar beet as they are the major crops produced in China. We began with extracting the changing trends of temperature and precipitation for China from the downscale simulation of Liang and Yan (2016), based on the RCP scenarios of Intergovernmental Panel on Climate Change Fifth Assessment Report (IPCC AR5) (IPCC, 2014). Both RCP 8.5 and RCP 2.6 scenarios are modeled in this study as the worst and best climate change scenario, respectively. In Liang and Yan (2016), several global circulation models (GCM), provided by CMIP5, are applied to project monthly temperature and precipitation during 2010–2100 in each province of China with base year of 1980–2010. Then we estimate both annual average and standard deviation of temperature and precipitation during each crop's growth season. The projections show that compared to 2012, the annual average temperature and precipitation during growing season of each crop will increase significantly in 2020–2050, while the standard deviation of annual precipitation will increase significantly for each crop (see Appendix Fig. 1). This shows both temperature and precipitation will increase, but the latter will have more annual fluctuation during crop growing seasons of the future years.

We obtain the changes in annual crop yield under climate change in China from a unique econometric estimation of Wang (2016). The study used China's provincial panel data to estimate climate change impacts on the yields of different crops in terms of changes in annual temperature, precipitation and their standard deviations during the growth season of major crop producing provinces, while controlling for differences in agriculture inputs and technology progress (Appendix Table 2). The study finally illustrated a nonlinear correlation between climate variables and crop yield, and extrapolated the annual changes of China's crop yields under IPCC's four RCP scenarios for the period 2010–2050 (Table 1).[3]

The physical impacts of climate change on crop yields in China vary considerably among crops and are shown in Table 1. Wheat, rice, peanut, and sugar beet are projected to experience yield reductions under both RCP 8.5 and RCP 2.6 scenarios, with wheat expected to bear the highest yield loss. Specifically, wheat yield would decline significantly in 2050 i.e., by 4.83% under RCP 2.6 and 9.39% under RCP 8.5. Next to wheat, rice yield would have moderate yield reduction in 2050 of 1.34% under RCP 2.6 and 2.60% under RCP 8.5. Due to the changing climate, the yields of peanut and sugar beet are projected to drop only marginally. Other crops, including cotton, rapeseed, soybean and maize may see positive yield impacts from climate change. Among these crops, cotton will have the most significant increase in yield due to climate change, followed by rapeseed, soybean, and maize. Under RCP 8.5, cotton yield is projected to increase by 1.74% in 2030 and 4.24% in 2050. Compared with cotton, the positive impacts of climate change on soybean and maize yield are rather small such that their yields would increase by $<0.5\%$ in 2050 under RCP 8.5. To concord with crop sectors in CAPSiM model, we estimate oilseed yield change as the average of changes in rapeseed and peanut yields weighted by harvest area in 2015.

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[3] The interested readers can contact the corresponding author about the data source, detail estimation method and results.

Table 2
The annual impacts of climate change on crop yield in the rest of the world to 2050 (%).

	RCP 2.6				RCP 8.5			
	Rice	Wheat	Maize	Soybean	Rice	Wheat	Maize	Soybean
Australia & New Zealand	−0.02	−0.27	−0.12	−0.09	−0.19	−0.40	−0.28	−0.28
Japan	0.15	−0.09	−0.04	0.01	0.16	0.09	−0.18	−0.01
Korea	−0.01	0.23	−0.35	−0.03	−0.06	0.24	−0.66	−0.07
Indonesia	−0.01	0.00	−0.17	−0.08	0.00	0.00	−0.33	−0.13
Malaysia	−0.04	0.00	−0.17	0.12	−0.08	0.00	−0.42	−0.05
Philippine	−0.03	0.00	−0.18	−0.11	−0.05	0.00	−0.38	−0.24
Thailand	−0.05	0.05	−0.38	−0.23	−0.14	−0.00	−0.79	−0.31
Vietnam	−0.09	0.03	−0.22	−0.12	−0.18	0.03	−0.57	−0.26
Canada	0.00	0.05	0.15	0.17	0.00	−0.03	0.05	0.14
USA	−0.09	0.06	−0.22	−0.03	−0.27	0.07	−0.63	−0.21
Argentina	−0.03	−0.10	−0.05	−0.01	−0.12	−0.15	−0.25	−0.15
Brazil	−0.07	−0.04	−0.14	−0.13	−0.18	−0.18	−0.41	−0.34
EU_28	0.07	0.13	−0.03	0.08	0.04	0.06	−0.20	0.00
Rest of World	−0.07	0.05	−0.13	−0.15	−0.20	−0.01	−0.37	−0.37

Note: The base year is 2012.
Source: Simulation results from IFPRI.

2.2. Climate change shocks for biophysical yields of crops in the rest of World

The estimates on climate change impacts on crop yields for other countries are based on the biophysical simulations of a process-based crop model by the International Food Policy Research Institute (IFPRI). Annual yield changes of major crops, i.e., wheat, maize, rice, and soybean, in response to climate change are listed in Table 2 for the world's14 regions/countries. The yield changes of these crops are estimated using the Decision Support System for Agrotechnology Transfer (DSSAT) model and IPCC RCP scenarios for 2011–2050 with the base year of 2010. As shown in Table 2, climate change is projected to cause different yield changes among major crops in other countries under RCP 2.6 and RCP 8.5. Most countries would see a reduction in their annual average crop yields in response to climate change. Notice that USA, Argentina and Brazil, who are also the main exporters of maize and soybean, would have serious yield losses by 2050. Particularly, the annual average decrease in maize yield will be >0.4% for USA and Brazil, and 0.2% for Argentina under RCP 8.5. While the soybean yield will fall by >0.3% for Brazil, and >0.15% for USA and Argentina under RCP 8.5. The supply of these crops, also regarded as the major agricultural commodities imported by China, will be significantly threatened by climate change, ensuing a major global hike in their respective prices. Furthermore, we can also find that Canada would benefit from climate change in both maize and soybean yield by 2050 (increase by 0.05% per annum (p.a.) for maize and 0.14% p.a. for soybean under RCP 8.5). Moreover, most countries are found to have negative impacts of climate change on rice and wheat yields by 2050. Australia and New Zealand are projected to experience the biggest decrease in wheat yield (−0.40% p.a.), while USA have the biggest decrease in rice yield (−0.27% p.a.) under RCP 8.5. At the same time, Japan and European Union would benefit from climate change in terms of both rice and wheat yields under RCP 8.5.

Here we want to note that using climate shocks for China and the rest of world from dissimilar sources in this study can result in some inconsistencies. In fact, our motive is to include the effects of adaptation by farmers to reflect the real impacts of climate change, which we do through our econometric estimation for China. As China is our main study region, our priority is to make sure that the results of China have high accuracy. However, due to the unavailability of data for all the other countries, it is impossible to do the econometric estimation for the rest of world, for whom we use the simulation results from a biophysical model. Additionally, a comparison between our econometric results and the biophysical simulation results for China could reveal if there are large discrepancies between both sets of yield shocks. Here, we find that the two methods have similar results for the impacts (for example, under RCP8.5 in 2050, the econometric results for rice and soybean are −2.6% and 0.42% respectively; while the biophysical simulation results for rice and soybean are −3.2% and − 0.87% respectively). We think that the crop yield losses for other countries without consideration of adaptation might be slightly overestimated, so the results of our study might also be somewhat overestimated in our simulations of economic models.

3. Simulation methodology and scenarios

3.1. Simulation Model

In order to consider the domestic market responses to climate change impacts on China's agriculture, we have used a widely recognized agricultural partial equilibrium model (China Agriculture Policy Simulation Model, CAPSiM). The model was developed at the China Center for Agriculture Policy (CCAP) in the mid-1990s as a partial equilibrium model for analyzing policies affecting

China's agricultural production, consumption, prices, and trade (Huang & Li, 2003; Li & Huang, 2004). Since then, CAPSiM has been periodically updated and expanded, while the recent versions of the CAPSiM are designed to track changes in trade liberalization, urbanization, and climate change (Yang, Huang, Rozelle, & Martin, 2012; Huang et al., 2017). In CAPSiM, the crops sectors are more disaggregated and account for >90% of China's agricultural output. The model covers 21 agricultural commodities: including rice, wheat, maize, other coarse grain, sweet potato, potato, soybean, edible oil crops, cotton, vegetables, fruits, other crops, as well as six livestock products and three fishery sectors. The accompanying database of CAPSiM has been updated to 2015 according to the official statistics from China's National Bureau of Statistics and National Customs. CAPSiM can investigate the climate change impacts on China's agriculture to reveal the response from local markets, with the assumption that climate change effects from other countries do not transcend to China via trade.

Then to consider both the market and trade responses simultaneously, we also used the linked national and global equilibrium model (CAPSiM-GTAP) to assess the climate change impacts on agriculture. GTAP (Global Trade Analysis Project) model is a well-recognized multi-country, multi-sector computable general equilibrium model, and is often used for international trade analysis (Hertel, 1997). GTAP model has the advantage of simulating global price changes of agricultural commodities in response to climate change. However, in contrast to the China module of GTAP model, the CAPSiM model also has the following advantages: first, CAPSiM is a partial equilibrium model of China's food market presenting the supply and demand in volumetric (quantity) terms. Whereas, GTAP model is a general equilibrium model using dollar values for supply and demand relationships. For food markets, quantity impacts are very important for capturing the effects of climate change or any other shocks. This is one of the reasons that researchers usually rely on partial equilibrium models to project the quantity level results for the future (for example, FAO-OECD Agricultural Outlook; USDA Agricultural Projections). Second, most of the key parameters of CAPSiM model are derived from the empirically based studies conducted by CCAP, in contrast to generalized parameters used in GTAP model. Third, the base data of CAPSiM has been updated to more recent year (2015) reflecting China's market structure more precisely, while the latest database of GTAP model is based on market conditions in 2011. Moreover, the CAPSiM based projections on future food market for China are also widely accepted in China. We, therefore, have higher confidence in CAPSiM results in comparison to results from the China module of GTAP model. Overall, a linked model between CAPSiM and GTAP offers the best of both individual models such that we can transmit the effects of other countries' climate shocks to China via trade, while simultaneously using a more precise and detailed national economic model. Finally, to map the sectors between the CAPSiM and GTAP model, the GTAP version 9 database is aggregated into 15 regions and 25 sectors (Appendix Table 1).

Following Horridge and Zhai (2005), we established a linkage module between CAPSiM and GTAP model to evaluate the climate change impacts while considering both the responses of market and trade concurrently. The key idea of CAPSiM-GTAP linking method, as proposed by Horridge and Zhai (2005), is to transmit the global price changes from GTAP model into the national model through trade. Specifically, in CAPSiM, the global demand price for China's food export and the global supply price for China's food import are exogenous and are updated using the projection of OECD-FAO agricultural outlook (OECD/FAO, 2018) under the baseline scenario. Under our proposed first scenario (climate change scenario considering only domestic market response under RCP 2.6 and RCP 8.5 using CAPSiM), as we do not consider the global price changes caused by climate change in other countries, we keep the global demand price for China's food export and the global supply price for China's food import same as the baseline scenario (only use CAPSiM model as given in Appendix Table 3). Under our proposed second scenario (climate change scenarios considering both the domestic market response and the trade response using linked CAPSiM – GTAP model), we proceeded in three steps: 1) we assume that climate change only affects China and therefore we only shock China's crop yields and keep the crop yields for all other countries unchanged in GTAP model. Ideally, if the structure for China's economy in both CAPSiM and GTAP model were similar to each other, we would expect to have the same results from this simulation as in the first scenario. However, as China is represented differently in both models, we anticipate that our CAPSiM model can better reflect China's food market than the China module in GTAP model. 2) We assume that climate change strikes all over the world, so we shock all countries' crop yields in GTAP model. 3) We take the difference of global food prices between step 1 and 2 (step 2 - step 1) as akin to the impacts of climate change in other countries on China's food market. Thus, we incorporate the difference in global price between the two steps into CAPSiM to reflect the impacts of climate change in other countries on China's food market through trade (of course, under the second scenario, we shock both the crop yields and the global food prices– the global demand price for China's food export and the global supply price for China's food import– in CAPSiM) (see Appendix Table 3).

3.2. Baseline scenario

For analyzing the impacts of climate change on China's agriculture, we establish a baseline scenario towards 2050 for both GTAP model and CAPSiM. The GTAP baseline is constructed by recursively updating the database such that given GDP targets are met through given exogenous estimates of factor endowments i.e. skilled labor, unskilled labor, capital, natural resources, and population. The procedure and the exogenous macro assumptions are discussed in details in Hertel (1997) and Walmsley, Dimaranan, and McDougall (2006). For the baseline in CAPSiM, several key assumptions are used for the baseline scenario concerning GDP growth, population growth, urbanization rate, urban and rural households' income growth, and agricultural technology advancement (for in depth discussion see Huang et al., 2017).

In the baseline projection, China's agricultural production will continuously increase in the future, with a simultaneous and significant rise in the imbalance between agricultural production and demand. Demand for feed grains will grow faster than their domestic production, leading to declining self-sufficiency rates.[4] By 2050, domestic production of rice and wheat will almost meet China's domestic demand, both reaching high self-sufficiency rates of over 95%. However, for maize, which experienced over-supply in recent years mainly due to policy interventions in China, the demand will increase significantly in coming decades due to rising demand by livestock production. If China does not implement tariff rate quota (TRQ)[5] in the future, China's maize import is projected to surpass 40 million tons by 2050, leading to a self-sufficiency rate of < 85%. Similar to maize, soybean import is projected to cross 100 million tons in 2050, resulting in a self-sufficiency rate of < 10% for China. Demand for sugar and edible oils will be significantly higher than their respective domestic productions, leading to decreasing self-sufficiency ratios for both commodities. In contrast, domestic production of vegetables and fruits is projected to increase in pace with domestic demand, ensuring almost full self-sufficiency in the future.

China's livestock supply-demand balance mostly depends on policies governing feed grain trade and grassland development. CAPSiM projection shows that aquatic products will almost keep supply-demand balance requiring minimal import. However, livestock self-sufficiency may undergo significant changes due to many uncertainties surrounding its demand and supply. If China were to remove the import limitations on feed grain and thus make way for domestic livestock production fed by cheap imported feed grain, pork and poultry could retain high self-sufficiency rates. In contrast, livestock imports in China will significantly increase mainly due to maize import limitation (e.g. TRQ) and inadequate grassland development. In the latter situation, CAPSiM projections show that in addition to considerable pork and poultry imports, China will import large quantities of beef, mutton and dairy by 2050, and will have self-sufficiency rates ranging over 70–80% across different livestock products.

3.3. *Climate change scenarios*

In the CAPSiM settings, percent change of crop yield is a linear function of the percentage change of crop price, input prices (including fertilizer, land, and labor), as well as other factors (such as climate change conditions). Thus, climate change impacts on crop yields discussed in section 2 are transmitted into the crop production module in the CAPSiM through shifting the crop yield changes. Meanwhile, crop yield changes are simulated in GTAP model as the shift to total factor productivity of the crop sectors. In Roson and Mensbrugghe (2010), variations in agricultural yield are modeled as changes in multifactor productivity for agricultural activities, so that output volumes vary despite using the same mix of production factors (they used the ENVISAGE model—a general equilibrium economic model). In Nelson, Mensbrugghe, et al. (2014), for the general equilibrium economic models, the yield shocks of climate change are implemented as shifts in the land efficiency parameters of the sectoral production functions; while for the partial equilibrium models, the shocks were introduced as additive shifters in a yield or supply equation. Robinson, van Meijl, Valin, and Willenbockel (2014) also discussed the incorporation of yield shocks into general/partial equilibrium models. It can thus be concluded that regardless of the model type i.e. general or partial equilibrium, some studies chose to shock TFP; while the others shock land efficiency. In our study, for the CAPSiM, the shocks are introduced as additive shifters in crop yield; for GTAP model, crop yield changes are simulated as changes in total factor productivity (TFP) of these crop sectors. Because we used the linked model, we kept the shock methods consistent between CAPSiM and the China module in GTAP.

We constructed two separate climate change scenarios to simulate the impacts of climate change on China's food supply, prices, trade and self-sufficiency, and examine the market and trade responses. 1) Climate change scenarios with considering market response (using CAPSiM) under RCP 2.6 and RCP 8.5; 2) climate change scenario with considering both the market response and the impacts on rest of the world (ROW) (using linked CAPSiM-GTAP model). Comparing changes in biophysical crop yields with changes in crop production estimated using CAPSiM only could reveal the response of domestic market in buffering climate change impacts, because CAPSiM model keeps food import and export prices unchanged. The linked CAPSiM–GTAP model, on the other hand, allows the food import and export prices to change with changes in global food prices, which are projected by the GTAP model. A comparison between the results from CAPSiM and CAPSiM-GTAP model could reveal the response of global trade in buffering climate change impacts (Appendix Table 3).

4. Simulated results for climate change impacts on China's agriculture

The following section describes simulated results for climate change impacts on China's agricultural production, prices, and trade based on the CAPSiM and the linked CAPSiM-GTAP simulations in 2015–2050. Comparing the CAPSiM results with the biophysical impacts of climate change can reveal the response of domestic market in buffering climate change impacts. Then the assessment on climate change impacts considering the response of global trade will be discussed based on the simulation results from the linked CAPSiM-GTAP model. To this end, percentage changes indicated in the text refer to the difference of agricultural production, prices and trade without and with climate change.

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[4] The self-sufficiency rate is defined as the ratio of domestic food production to food supply (production plus net import)

[5] The maize import quota is set at 7.2 Mt. in 2017, and a 65% tariff will be imposed on the imported maize beyond the quota.

Table 3
The impacts of climate change on crop production in China under RCP 2.6 and 8.5 (%).

	RCP 2.6				RCP 8.5			
			CAPSiM-GTAP		CAPSiM		CAPSiM-GTAP	
		2050	2030	2050	2030	2050	2030	2050
Rice	−0.27	−0.46	−0.28	−0.55	−0.30	−0.67	−0.21	−0.22
Wheat	−0.92	−1.61	−0.97	−2.21	−1.95	−4.28	−1.92	−4.03
Maize	0.24	0.20	0.40	3.58	−0.11	−0.64	1.01	1.93
Soybean	0.38	0.29	1.48	2.98	0.00	−1.47	4.26	16.75
Cotton	−0.48	0.74	−0.10	2.35	2.07	3.57	2.49	9.30
Oilseed	0.06	0.17	0.11	0.23	0.19	−0.10	0.41	0.72
Sugar	−0.11	−0.21	−0.15	−0.45	−0.32	−0.66	−0.53	−1.53

Note: The base year is 2012.
Source: CAPSiM and CAPSiM-GTAP simulations.

4.1. Climate change impacts on China's agricultural production

Climate change will have varying impacts on China's future crop production. From the CAPSiM simulations, rice, wheat, and sugar will have production losses due to climate change both under the RCP 2.6 and RCP 8.5 (Row 1–2, Table 3), wherein wheat is projected to have the highest production reduction by 2050 (−1.61% under RCP 2.6 and − 4.28% under RCP 8.5). Notice that the climate change impacts on production of these crops are less than the yield losses estimated by the econometric model. Wheat production loss in 2050 under RCP 8.5 (4.28%) is less than half the yield loss due to climate change (9.39%). This indicates that the domestic market evidently plays an important role in dampening climate change impacts. When the climate change hits crop production, the farmers improve their production practices in light of their previous experience under similar situations, which at least partially reduces the production losses caused by climate change. Farmers are likely to increase frequency and strength of field management, such as irrigation, weeding, adopting drought-resistant varieties, among others. These results signify the important role that the domestic market can play in buffering climate change impacts.

More interestingly, some crops with positive yield changes will end up having production reduction (Table 3). For example, by 2050 maize will have slight yield increase under RCP 8.5 (0.31%, Table 1), however, its production is projected to decrease under RCP 8.5 (−0.64%, Table 3). The mechanism at action is that rice and wheat are mostly domestically produced and their yields, in contrast to maize, are more seriously affected by climate change in China. Keeping in mind the importance of rice and wheat, the farmers would increase their production by not only improving field management, but also by taking agricultural inputs (e.g., land and labor) away from the positively affected crops (like maize). As a result, the positive impacts of climate change on maize yield would be offset by declining inputs of land and labor, and even render maize output to decline. Moreover, both soybean and oilseed crops have slightly positive output impacts due to climate change, except in 2050 under RCP 8.5 (Table 3). Similar to maize, the substitution effects between crops would offset the slight yield increase for soybean and oilseed crops brought by climate change. In

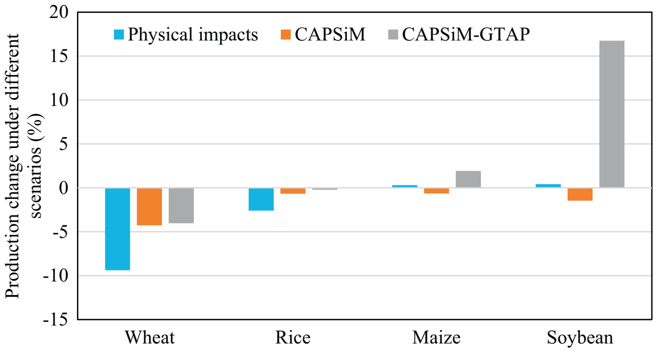

Fig. 1. Comparison of crop physical impacts and production changes (%) in the CAPSiM and CAPSiM-GTAP model in 2050 under RCP 8.5 (the base year is 2012).

Table 4
The impacts of climate change on crop price in China under RCP 2.6 and 8.5 (%).

	RCP 2.6				RCP 8.5			
	CAPSiM		CAPSiM-GTAP		CAPSiM		CAPSiM-GTAP	
	2030	2050	2030	2050	2030	2050	2030	2050
Rice	1.75	2.92	1.52	2.91	1.61	4.55	2.81	7.41
Wheat	3.85	6.83	3.71	7.17	5.49	15.47	8.56	22.91
Maize	0.16	0.31	0.23	6.35	0.00	0.23	2.95	8.86
Soybean	−0.02	−0.02	1.64	6.73	−0.03	0.10	7.06	30.27
Cotton	0.28	−0.27	1.02	3.82	−0.58	−0.77	0.54	10.42
Oilseed	−0.05	−0.15	0.11	0.42	−0.27	0.10	0.56	3.00
Sugar	0.24	0.32	0.24	0.58	0.23	0.51	0.81	2.06

Note: The base year is 2012.
Source: CAPSiM and CAPSiM-GTAP simulations

addition, cotton production would benefit from climate change by 2050 by relatively lower margins under both RCP 2.6 (0.74%) and RCP 8.5 (3.57%). This is because cotton yield increases are much large by 2050 (1.74% for RCP 2.6 and 4.24% for RCP 8.5) although partly offset by the substitution effects.

Further, the climate change impacts in other countries will cause cross border ripple effects and will further soften the impacts of climate change on China's agriculture (Fig. 1). For example, while soybean production in 2050 will decrease slightly under RCP 8.5 (−1.47%) in the CAPSiM results, the same is projected to significantly increase (16.75%) in the CAPSiM-GTAP linkage model. This effect could be attributed to opposite impacts of climate change on soybean yields in China and the other countries. While soybean yield is projected to increase slightly in China (Table 1), the yields for main exporters, such as Brazil, Argentina, and USA, are all projected to decrease significantly (Table 2). Soybean output reduction in the aforementioned global exporters would cause severe shortage in the global market, which will further incentivize the farmers in China to improve soybean production. Consequently, China's soybean production would expand in the CAPSiM-GTAP results. A similar effect of international trade can also be found on maize production, which has a slight decrease in the CAPSiM results in 2050 under RCP8.5 (−0.64%) but a slight increase in CAPSiM-GTAP results (1.93%) (Fig. 1). Although both rice and wheat outputs would decline in CAPSiM simulation under RCP 8.5, the output reductions in the CAPSiM-GTAP results are lower than those in the CAPSiM results (Fig. 1). For example, wheat output would reduce by 4.28% in the CAPSiM results in 2050 under RCP8.5, and by 4.03% in the CAPSiM-GTAP results. This set of results shows that after we consider the role of international trade in climate change assessment, the negative impacts of climate change on China's agriculture will be further reduced, at least partially.

4.2. Climate change impacts on China's agricultural prices

The prices of the negatively affected crops under climate change would increases in domestic market by 2030 and 2050 both under RCP 2.6 and RCP 8.5. In CAPSiM simulation, the market clearing mechanism dictates that when climate change causes yield

Table 5
Impacts of climate change on crop net import under RCP 2.6 and 8.5 (%).

	RCP 2.6				RCP 8.5			
	CAPSiM		CAPSiM-GTAP		CAPSiM		CAPSiM-GTAP	
	2030	2050	2030	2050	2030	2050	2030	2050
Rice	9.86	22.16	16.31	61.88	15.35	43.93	1.66	−50.37
Wheat	10.86	20.33	13.22	43.11	22.87	56.81	16.69	30.87
Maize	−1.11	−0.47	−1.50	−10.87	0.64	1.69	−4.74	−1.70
Soybean	−0.06	−0.05	−0.99	−3.31	−0.02	0.28	−3.75	−13.71
Cotton	0.60	−0.62	0.12	−1.97	−2.60	−3.00	−3.12	−7.81
Oilseed	−0.11	−0.35	−0.15	0.80	−0.38	0.46	−0.62	0.14

Note: The base year is 2012.
Source: CAPSiM and CAPSiM-GTAP simulations

Table 6

Impacts of climate change on crop self-sufficient rate under RCP 2.6 and 8.5 (absolute percent change).

	RCP 2.6				RCP 8.5			
	CAPSiM		CAPSiM-GTAP		CAPSiM		CAPSiM-GTAP	
	2030	2050	2030	2050	2030	2050	2030	2050
Rice	−0.05	−0.11	−0.08	−0.29	−0.08	−0.21	−0.01	0.23
Wheat	−0.24	−0.48	−0.28	−1.00	−0.50	−1.37	−0.37	−0.78
Maize	0.16	0.13	0.23	2.85	−0.09	−0.46	0.70	0.71
Soybean	0.06	0.04	0.31	0.77	0.00	−0.21	1.04	4.02
Cotton	−0.27	0.34	−0.05	1.07	1.15	1.63	1.38	4.24
Oilseed	0.02	0.07	0.04	−0.08	0.08	−0.08	0.15	0.08
Sugar	−0.06	−0.13	−0.08	−0.26	−0.18	−0.40	−0.27	−0.83

Note: The base year is 2012.

Source: CAPSiM and CAPSiM-GTAP simulations

reduction, domestic production of the crops will decrease, and consequently, the inadequate domestic supply will raise the local prices. Rice, wheat, and sugar would have their local price to increase by highest margins in response to yield reduction caused by climate change. For example, wheat would have the largest price increase in 2050 of around 6.83% under RCP 2.6 and 15.47% under RCP 8.5 (Table 4), because it would experience the worst yield damage. Rice will see a moderate price hike by 2050 of 2.92% under RCP 2.6 and 4.55% under RCP 8.5. Moreover, the domestic prices of all other crops will also increases in 2050 under RCP 8.5 except for cotton. Consistent with its positive yield shock, cotton would have a reduction in local price of 0.58% in 2030 and 0.77% in 2050 under RCP 8.5. However, while maize will experience slight yield increase under both RCP 2.6 and RCP 8.6, its domestic price for China will increase marginally, mainly due to the substitution effects mentioned in section 4.1.

As compared to the CAPSiM results, the domestic prices for all the crops will increase by much higher margins if we consider the response of international trade using linked CAPSiM-GTAP model (Table 4). Climate change have significant impacts not only on crop prices in China, but also on the crop prices in other countries. The global prices would increase sharply for the crops with high negative yield changes due to climate change such that China will be unable to import these crops at the new price levels. As a result, the reduced supply will lead to a sharp rise in China's domestic crop prices. Our results show that domestic prices of wheat and soybean would further increase greatly in the linked CAPSiM-GTAP results, mainly because China's main trading partners will suffer more severe yield reduction for these crops.

4.3. Climate change impacts on China's agricultural trade and self-sufficiency

In addition to crop production and prices, climate change will also significantly affect China's trade in these agricultural commodities. In the CAPSiM results, the crops with negative yield shocks, especially rice and wheat, will see increase in their net imports in 2030 and 2050 (Table 5). Wheat is projected to have the most significant increase in net import in 2050 both under RCP 2.6 (20.33%) and RCP 8.5 (56.81%). Compared with around 4% production reduction of wheat in 2050 under RCP8.5, the seemingly large percentage increase (56.81%) in wheat net import is not actually large in volume terms as wheat import has very small share in China's total wheat demand. Other crops, including cotton, oilseed, and soybean, are expected to have slight reductions in their net imports in response to climate change, as their respective yields would increase slightly in China.

On the other hand, net imports of the crops in the CAPSiM-GTAP results differ from those in the CAPSiM results. Though China's domestic prices of crops would rise due to climate change, global crop prices would also increase due to reduced production in several major producing countries. If the global crop prices increase more than the increase in China's crop prices, China would inevitably reduce its net imports of the crops. For example, in 2050 under RCP 8.5, China's net import of wheat is projected to increase by 56.81% in the CAPSiM results, but the increase is reduced to 30.87% in the CAPSiM-GTAP results (Table 5). Similar to wheat, other crops also have lower net imports in the linked CAPSiM-GTAP results, e.g., China's net import for soybean will fall by 13.71% (>10 Mt) in 2050 under RCP 8.5 as compared to 0.28% increase of net import for soybean in the CAPSiM results.

Though climate change would threaten China's self-sufficiency in many agricultural commodities, the crop self-sufficiency rates will increase when considering the climate shocks in other countries. Compared to the baseline scenario, crops experiencing negative yield shocks will have decreasing self-sufficiency rates in the CAPSiM results (Table 6). Among these crops, wheat has the largest decrease in self-sufficiency rate in 2050 (by 0.48 percentage points under RCP 2.6 and 1.37 percentage points under RCP 8.5), which is consistent with the fact that wheat happens to be the crop with the most significant output reduction and net import increase. Under RCP 8.5 scenario, all other crops will have lower self-sufficiency rates by 2050 compared to 2010, except for cotton, which benefits most from climate change. The overall self-sufficiency rate of major cereals[6] in 2050 would decrease by 0.21 percentage points under RCP 2.6, and 0.65 percentage points under RCP 8.5. On the other hand, in the CAPSiM-GTAP results, all crops would have higher self-sufficiency rates as compared to the corresponding numbers in the CAPSiM results. For example, soybean's self-

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[6] Major cereals include rice, wheat, and maize.

sufficiency rate would increase by 0.46 percentage points (0.77–0.31) in 2050 under RCP 2.6 and 2.98 percentage points (4.02–1.04) under RCP 8.5 when considering the climate shocks in other countries. These results further show that when considering the climate shocks in other countries, China's agricultural self-sufficiency will increase.

5. Conclusions and policy implications

Agriculture, an important sector in China, is mandated to feed over 1.3 billion people of the country and provide important inputs for many industries. Such prospect, however, is likely to be threatened by the yield damages caused by climate change. The previous studies on climate change effects on agriculture in China did not account for the buffering capability of local market and international trade. To fill this gap in the literature, we assess climate change impacts on China's agriculture and responses from market and trade using an agricultural partial equilibrium model, CAPSiM, and its linkage model with GTAP model (CAPSiM-GTAP). In this paper, the climate change impacts are examined during 2020–2050 under RCP 2.6 and RCP 8.5 scenarios. Our results show that climate change would have significant effects on agriculture production of China but with large variations among crops. Under the worst climate change scenario, i.e., RCP 8.5, wheat production is projected to decline by around 9.4% by 2050, the biggest production reduction among the crops. The results also suggest some evidence of the adaptation capability of market response to climate change wherein farmers intensify agronomic inputs, improve field management and adjust production structure. When we add the market response to the mix, production loss for wheat under RCP8.5 reduces to only 4.3%. Global agricultural trade provides additional adaptation capability to climate change damage for China, where the country can further avoid crop production losses and raising its self-sufficiency of important food crops, at least partly. When considering both domestic market and international trade responses simultaneously, wheat production loss under RCP 8.5 would reduce further to around 4%.

Our results have important policy implications for national adaptation plans. First, the adaptation policies should prioritize the crops based on the severity of production losses. Specifically, the investments in adaptation measures should be channeled to more negatively affected crops and to the ones that play more vital role in national food security. Secondly, the policies facilitating market integration and free trade would help to buffer climate change impacts. In general, when climate change strikes, farmers intrinsically increase agronomic inputs (labor, irrigation, pesticide, and others) to adapt to climate change, because they expect high prices in light of their previous experience of high price due to climate change. More so, if the domestic market and international trade are free of distortions and barriers, wherein the price will increase to some reasonable extent in times of climate change. Then in the subsequent crop season, farmers will increase inputs as high as they can to prevent production losses based on their experience with the price increase during previous climate changes. On the contrary, if the market is cluttered with interventions or the trade is restricted, farmers cannot experience general price change due to previous climate changes, and when climate continues to change, they may not increase inputs to that extent. Thus, in addition to the hard measures for adaptation (such as investment in irrigation system), the soft measures (e.g. reducing market intervention, reducing import tariffs and import quotas or other trade barriers) are recommended in order to reduce production damages caused by climate change. Thirdly, to optimize adaptation plans, we need to learn more from farmers who respond to changing climate according to the market and trade signals, and then improve and mainstream the practices adopted by farmers into national adaptation development plans. The farmer's adaptation measures carried by themselves are much important in adapting to climate change, including increasing number of irrigations and other field management measures. The only thing we need to do is to keep markets free and remove trade barriers.

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Appendix A. Appendix

Appendix Table 1

GTAP region and sector aggregation.

Regions				
China	Australia & New Zealand	Japan	Korean	Indonesia
Malaysia	Philippian	Thailand	Vietnam	Canada
USA	Argentina	Brazil	EU	Rest of world
Sectors				
Rice	Processed Rice	Wheat	Maize	Other grains
Vegetables & fruits	Soybean	Other oilseeds	Sugar	Plant fibers
Other crops	Cattle	Pork & chicken	Milk	Wool
Vegetable oils	Beverages & tobacco	Processed food	Fish	Extraction
Light Manufacturing	Heavy Manufacturing	Utilities & Construction	Transport & Communication	Services

Appendix Table 2

The estimated impacts of climate change on crop yields in China.

	Wheat	Rice	Maize	Soybean	Cotton	Rapeseed	Peanut	Cane	Sugar beet
Climate during growing season									
Temperature	−0.0675*	0.0431***	−0.0160	−0.0372	0.3366***	0.0251	0.0469	−0.3769	−0.1893
Temperature squared	0.0012	−0.0014***	−0.0015	0.0005	−0.0074**	−0.0020	−0.0001	−0.0004	0.0027
Precipitation	0.0005**	0.0001**	0.0005***	0.0014***	−0.0002	0.0012***	0.0002	−0.0022	0.0003
Precipitation squared	−0.0000007***	−0.0000001***	−0.0000002***	−0.00000072***	0.00000005	−0.0000007***	−0.0000001	0.00000061	−0.00000026
Climate variation in growing season									
Standard deviation of temperature	−0.0254**	0.0061	−0.0569***	−0.0176	−0.0327	−0.0087	−0.0513*	0.1423	−0.0400
Standard deviation of precipitation	−0.0015**	−0.0004***	−0.0011**	−0.0019***	−0.0026***	−0.0019*	−0.0011*	−0.0021	−0.0036*

Note: Robust standard errors in parentheses.

Source: Wang, 2016.

*** $p < 0.01$.

** $p < 0.05$.

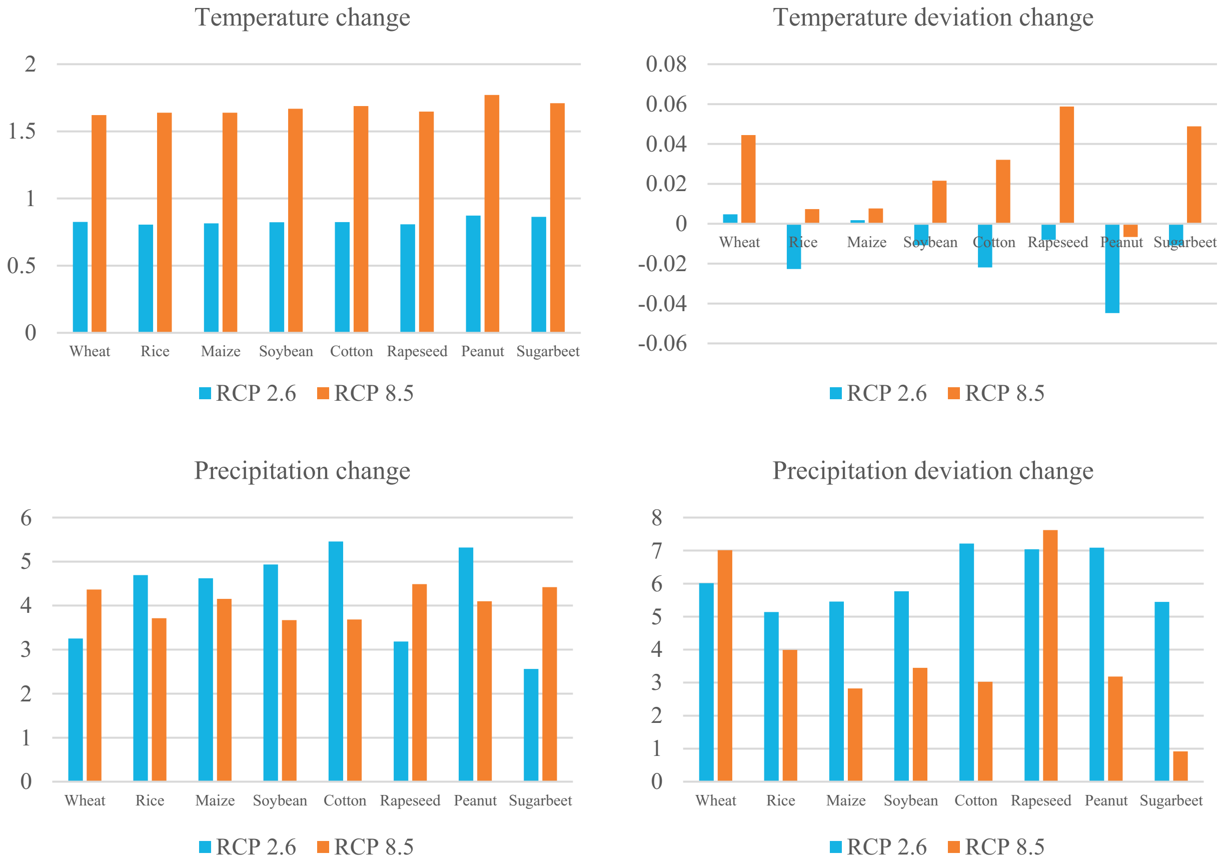
* $p < 0.1$.

Appendix Table 3

The summary of climate change scenario design.

Scenario 1 (CAPSiM)	• CAPSiM • Yield shocks to China only • No change in global price (same with baseline scenario)		
Scenario 2 (CAPSiM-GTAP)	Step 1 • GTAP model • Yield shocks to China only • Change in global price suggested by GTAP	Step 2 • GTAP model • Yield shocks to China & ROW • Change in global price suggested by GTAP	Step 3 • CAPSiM • Yield shocks to China • Change in global price suggested by the difference of global price change (Step 2–1)

*Note: results presented in tables from 3 to 6 are based on scenario 1 (CAPSiM) and Scenario 2 (CAPSiM-GTAP).



Appendix Fig. 1. Average and standard deviation change of temperature and precipitation for different crops during their growing season by 2050 (Base year: 2012).

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