A multi-model analysis of change in potential yield of major crops in China under climate change

Y. Yin, Q. Tang, and X. Liu

Abstract: Climate change may affect crop growth and yield, which consequently casts a shadow of doubt over China's food self-sufficiency efforts. In this study, we used the projections derived from 4 global gridded crop models (GGCropMs) to assess the effects of future climate change on the yields of the major crops (i.e. wheat, rice, maize and soybean) in China. The GGCropMs were forced with the bias-corrected climate data from 5 global climate models (GCMs) under the Representative Concentration Pathways (RCP) 8.5 which were made available by the Inter-Sectoral Impact Model Intercomparison Project (ISI-MIP). The results show that the potential yields of the crops would decrease in the 21st century without carbon dioxide (CO_2) fertilization effect. With CO_2 effect, the potential yields of rice and soybean would increase, while the potential yields of maize and wheat would decrease. The uncertainty of yields resulting from the GGCropMs is larger than the uncertainty derived from GCMs in the most part of China. Climate change may benefit rice and soybean yields in high-altitude and cold regions which are not in the current main agricultural area. However, the potential yields of maize, soybean and wheat may decrease in the major food production area. Development of new agronomic management strategies may be useful for coping with climate change in the areas with high risk of yield reduction.

Keywords: climate change; global gridded crop model; crop yield; uncertainty; China

1. Introduction

Global mean surface temperature has increased by 0.85 °C/100 yr over the period of 1880-2012, and it is likely to increase 1.5-2 °C at the end of the 21st century compared to the period of 1850-1900 (IPCC, 2013). In China, air temperature has increased by 0.5-0.8 °C during the past 100 years (Qin et al., 2005; Ren et al., 2005a; Ren et al., 2005b). At the end of the 21st century, surface temperature increases will exceed 2 °C with a probability of over 60% in all regions of China (Yang et al., 2014).

The impacts of climate change on crop yields and food production have prompted concern worldwide. There are numerous studies devoted to assessing the impacts of climate change on agriculture production over the past decades (Nicholls, 1997; Lobell et al., 2007; Tao et al., 2008b; Joshi et al., 2011) and future (Jones et al., 2003; Ewert et al., 2005; Lin et al., 2005; Tao et al., 2008a; Thornton et al., 2009; Liu et al., 2013b). Projections of changes in crop yields in China are widely reported using crop models (process-based or statistical) with GCM outputs which were

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generated for the Assessment Report of the IPCC (i.e. Parry et al., 2004; Tao et al., 2008a; Wang et al., 2011; Lv et al., 2013; Tao et al., 2013; Ju et al., 2013). It has been suggested that the yields of maize and rice would decline while wheat yield would increase in some regions in China as global mean temperature increases (i.e. Parry et. al., 2004; Lin et al., 2005; Rodomiro et al., 2008; Chavas et al., 2009; Challinor et. al., 2010; Ju et. al., 2013). Liu et al. (2013a) found that the production of major food crops in China might increase under various emission scenarios although the projections of climate change impacts on crop yields may be inherently uncertain (Asseng et al., 2013).

Understanding the effects of climate change on crop yield is important for developing adaptation and mitigation measures in agricultural regions of China. However, most existing assessments have been made based on a single crop model forced by climate change experiments generated for IPCC AR4. In addition, only a few studies have examined the impacts of climate change on crop yield in China using crop models forced by the latest climate change experiments generated for IPCC AR5. Furthermore, most of model experiments focused on model grids rather than administrative areas. It is difficult for the decision makers, who are more interested in the risk at the level of administrative area, to use the model results. Therefore, an assessment of change in potential crop yield at the administrative areas is needed for climate adaptation and mitigation.

Rice, maize and wheat are the major crops in China. The statistics from the National Bureau of Statistics of China (NBSC) (http://data.stats.gov.cn) show that the total area of the three major crops (rice, maize and wheat) occupies about 54% of the total cropland area in China. Soybean is a globally important crop, providing oil and protein. In recent years, China's rising demand for soybean has brought it to the top of the list of importers. China's import of soybean was 52 million tons in 2011, accounting for 58% of global soybean trade (Food and Agricultural Organization (FAO), http://faostat3.fao.org). Therefore, the yield changes of the four crops (i.e. rice, maize, wheat and soybean) are important for assessing the climate change impact on food security in China.

ISI-MIP is a community-driven modeling effort with the goal of providing cross-sectoral global impact assessments based on the newly developed climate scenarios (Warszawski et al., 2014). It provides an opportunity for assessing agricultural risks of climate change in the 21st century using the RCPs for IPCC AR5 (Rosenzweig et al., 2014; Elliott et al., 2014). The main objective of this study is to assess the effects of future climate change on the potential yields of the major corps (i.e. wheat, rice, maize and soybean) using the model outputs of 4 GGCropMs (i.e. EPIC, GEPIC, pDSSAT and PEGASUS) in ISI-MIP for administrative units in China. The model projected yield changes of the crops are illustrated at administrative area level and the uncertainty of model projections is analyzed.

2. Materials and methods

The global irrigated and rain-fed crop area data (MIRCA2000) were obtained from the Institut für Physische Geographie, Goethe Universitat (http://www.uni-frankfurt.de/45218031). The MIRCA2000 data consist of all major food crops including wheat, rice, maize and soybean (Portmann et al., 2010). The data sets refer to the period of 1998-2002 and have been made available with a spatial resolution of 0.5°×0.5° by ISI-MIP (Warszawski et al., 2014). The annual crop yields statistics from 1981 to 2010 were provided for each province of China by NBSC (http://www.stats.gov.cn/). There is one cropping season of per year in most of northern China and 2-3 seasons in southern China. The current GGCropMs cannot simulate well the multiple harvesting of rice (i.e. Priya et al., 2001; Xiong et al., 2014). For simplicity, we used the yield of a single harvesting time, although there are three different rice planting systems: single cropping rice, double cropping rice, and triple cropping rice in China (Mei et al., 1988). The yield from the single harvesting time was compared with the simulated potential rice yield of GGCropMs.

The simulated crop yield data were taken from 4 GGCropMs (EPIC, GEPIC, pDSSAT and PEGASUS) (see Table 1). These models contain different sub-model types and different parameterizations of soil and crop processes. The dissimilarities of the models and the consequent cautions needed in interpreting the model results are discussed in Rosenzweig et al. (2014). The GGCropMs were forced with the bias-corrected climatic data (Hempel et al., 2013) for the historical period 1971-2005 (except EPIC which was for 1980-2010) and the RCP 8.5 as the future climate scenario for 2006-2099 (except EPIC which was for 2011-2099) of 5 GCMs from the Fifth Coupled Model Intercomparison Project (CMIP5) (Taylor et al., 2012). All GGCropMs were run for two experiments: one takes into account the CO_2 fertilization effects and the other does not. In order to assess the performance of GGCropMs, the GGCropMs simulations with the CO_2 fertilization effect in the historical period were compared with the yield statistics from NBSC. Table 1 shows an overview of the 5 GCMs and 4 GGCropMs. All the 4 GGCropMs provided simulated yields of maize, rice, wheat and soybean except for PEGASUS which did not provide rice yield simulation. The yield simulations of EPIC were missing in 2066, 2067 and 2068. The GGCropMs provided the simulated crop yields for irrigated and rain-fed cropland.

For each 0.5°×0.5° grid, crop yield was calculated as the area-weighted yield in the irrigated and rain-fed portions of the grid according to the crop-specific irrigated and rain-fed areas. We divided China into 8 regions following administrative boundaries (Fig. 1). The average crop yield of a region was then calculated as the area-weighted yield in the irrigated and rain-fed portions of the grids in the region. The crop yield of each grid or region for each year was calculated for each GCM-GGCropM pair. There are 20 model pairs (5GCMs×4GGCropMs) for maize, wheat and soybean. Meanwhile, there are 15 GCM-GGCropM pairs for rice because the rice yield is missing in PEGASUS simulations. The 30-year moving averages of the crop yield from 1981-2099 were computed. The first 30-year moving average value was for the period of 1981-2010 (denoted as 1995, the center year of the period). The center year of the 30-year moving average was used to denote the 30-year period. The relative yield change was computed as the crop yield difference between a 30-year period in future and the historical period of 1981-2010, divided by the yield in the historical period. We computed the multimodel-ensemble medians (MMs) of the relative yield change from all the available GCM-GGCropM pairs, together with the inter-quartile range (the value of the 75th percentile minus that of the 25th percentile) of the multimodel ensembles.

The MMs of relative yield change with the CO_2 effect were calculated for the gridded outputs and for the prefectures in China at the end of the 21st century (2070-2099). If the MMs of relative yield change at the end of the 21st century is larger than 10% (smaller than -10%) and more than 75% model pairs support a positive (negative) change, the model projections suggest that the specific crop has a high resilience (risk) to climate change if no further adaptation measures were taken. The areas with high resilience (risk) to climate change for each crop were illustrated. Furthermore, the 25th percentile, instead of the MMs, was used to show the possible risk of the model projected worst-case.

The standard deviation (STD) of the relative changes from all the available GCM-GGCropM pairs was used to quantify the model uncertainty. The model uncertainties caused by GGCropMs and

GCMs were evaluated separately. The standard deviation of the relative change from 4 GGCropMs was calculated for each GCM. The averaged GGCropM standard deviation of the 5 GCMs was then used to assess the model spread caused by GGCropMs. Likewise, the averaged GCM standard deviation of 4 GGCropMs was used to assess the model spread caused by GCMs.

3. Analysis and Results

3.1 Crop area in China

Fig. 1 shows the planting areas of maize, rice, soybean and wheat in China today. The maize planting area is mainly distributed in Northeast China (NEC), North China (NC) and Southwest China (SWC). The rice planting area spreads across eastern China with large areas in East China (EC), South China (SC), NC and Central China (CC), and parts of Northeast China (NEC), Xinjiang (XJ) and Sichuan Province in SWC. The planting area of soybean is relative small compared to maize, rice and wheat. The main planting area is located in NEC and NC. The wheat planting area is mainly in NC, northern EC, parts of NEC and Sichuan Province in SWC.

3.2 Simulated and NBSC statistical yields in 1981-2010

Fig. 2 shows the simulated and NBSC statistical yields in China during 1981-2010. The NBSC yields were reported for each province. Apparently, the simulated patterns demonstrate that local details within each province while NBSC statistical patterns illustrate the yield difference among the provinces. The average yields for the 8 regions are listed in Table 2. Both the simulated and NBSC maize yields are high in the main maize planting areas such as NEC, NC, and NWC, and are relatively low in CC and SC (Fig. 2 a1,a2). It seems that GGCropMs overestimate maize yields in most areas of China, but underestimate maize yields in the high-altitude and cold regions such as the Tibetan Plateau. The simulated rice yield is lower than NBSC yield in all regions (Fig. 2 b1,b2). In EC, both simulation and NBSC data show high rice yield in a belt from southern NC to Sichuan Province in SWC, and low rice yield in the northern and southern provinces. In western China, GGCropMs simulation suggests lower rice yield in the high-altitude and cold regions than the low-altitude areas. The NBSC data show low rice yield in the high-altitude regions such as the Tibetan Plateau although the NBSC yield is generally higher than the simulation. The yield of soybean is lowest among the 4 major crops. The simulated soybean yields are generally higher than the NBSC yield in most areas of China (Fig. 2 c1,c2). In the main planting areas of soybean in NEC and NC, the simulated yield is about 90% and 65% of the NBSC yield, respectively. The yield of wheat is lower than those of maize and rice but higher than that of soybean (Fig. 2 d1,d2). The NBSC wheat yield is high in the main planting area such as NC, parts of NWC and XJ, but it is low in southern China. The simulated wheat yield shows some high values in the belt from NWC to Sichuan Province. Although, the model simulations are imperfect in terms of their ability to reproduce the NBSC statistical yield, they capture the difference between the crops. The comparison between model simulation and NBSC yield illustrates the inherent uncertainty of the state-of-art GGCropMs. Due to the large discrepancy between simulated yield and NBSC statistical yield in the historical period, the relative changes rather than the absolute differences are analyzed for future changes in crop yields.

3.3 Projected changes in crop yield

Fig. 3 shows the relative changes of the simulated yields of maize, rice, soybean, and wheat with and without the CO_2 fertilization effects in China. Without CO_2 effect, the simulated yields of maize, rice, soybean and wheat would decrease by more than 10% while the simulated wheat yield would decrease at most by about 25% at the end of the 21st century. With CO_2 effect, the simulated yields of rice and soybean would increase and yields of maize and wheat would decrease in the late 21st century. The projected change directions are generally consistent with previous studies (i.e. Lin et al., 2005; Ye et al., 2013; Ju et al., 2013). The relative change of maize yield is small (between -10% and 5%). The inter-quartile range of maize yields covering the zero change line throughout the study period indicates that the model agreement on the change direction is low. The simulated maize yield decreases by 3.3% in the late 21st century although the model uncertainty is high (Fig. 3a). There is a sustained high yield for rice and soybean beginning in the late 20th century. The simulated rice yield would increase by 8% in the 2070s and the most model pairs support an increasing change. The model agreement on the rice yield increase is very high before the 2040s, which suggests that climate change may benefit rice production in the next few decades. The MMs of the simulated rice yield remains at the high level after the 2070s although the model agreement becomes low. The simulated soybean yield would increase by 10% in the late 21st century and the most model pairs agree on the increase change (Fig. 3c). The simulated wheat yield shows little change before the 2030s, slightly increase during the 2040s to 2060s, and slightly decrease after the 2060s (Fig. 3d). The relative change in wheat yield is generally small (between -5% and 5%) and the agreement of the model pairs in the change direction is low.

Fig. 4 shows the relative changes in maize yield in the 8 regions of China. Without the CO_2 effect, the MMs of simulated maize yield would largely decrease in almost all the regions in China. With the CO_2 effect, the MMs of simulated maize yield would increase slightly before the 2060s and decrease slightly thereafter in the main maize planting region NWC. However, there is no model consensus on the change trend throughout the study period. In NC, another main maize planting area, the simulated maize yield would decrease slightly with high model agreement before the 2030s, which suggests that maize production in NC may decrease in the next few decades. The simulated maize yield would decrease largely after the 2050s although the model agreement on the decrease is low. In SC, there is a transition to a sustained lower yield for maize. The maize yield would decrease by 18% with high model agreement at the end of the 21st century. In contrast, the maize yield in NWC would increase by 5% before the 2030s. The maize yield after the 2030s would keep the high level after the 2030s in NWC although the model agreement becomes low. The simulated maize yields in EC, CC, XJ and SWC show a general decrease change with low model agreements.

Fig. 5 shows the relative changes in rice yield in the 8 regions of China. Without the CO_2 effect, the MMs of simulated rice yield would largely decrease in all regions in China. With the CO_2 effect, the simulated rice yield would continue to increase with high model agreement in NWC, SWC, XJ and NEC. The simulated rice yield would increase by about 5% in NC and XJ and by more than 10% in SWC, NEC and NWC at the end of the 21st century. In SC, CC and EC, the relative change in rice yield is generally small (<5%) and the model agreement on the change direction is low. These results indicate that climate change may benefit rice yield in northern and western China while its impact in southern and eastern China is inconclusive.

Fig. 6 shows the relative changes in soybean yield in the 8 regions of China. The simulated yield of soybean would decrease in all regions without the CO_2 effect. With the CO_2 effect, the simulated soybean yield would increase in NEC and NWC with high model agreement on the change direction. In NEC and XJ, the soybean yield would increase by more than 10% at the end of the 21st century. In NWC and SWC, the soybean yield would increase by about 7% and 14%. The relative change in soybean yield is generally small (<5%) with low model agreement in southern and eastern China (i.e. SC, EC and CC). The simulated soybean yield would increase slightly before the 2050s and decrease slightly thereafter with low model agreement in NC. These results indicate that climate change would benefit soybean yield in NEC, NWC and XJ but its impact in the other regions is inconclusive.

Fig. 7 shows the relative changes in wheat yield in the 8 regions of China. Without the CO_2 effect, the MMs of simulated wheat yield would decrease by more than 13% in all regions of China at the end of the 21st century. With the CO_2 effect, the simulated wheat yield would decrease slightly with high model agreement on the change direction in the next two decades in the NC region, the main wheat planting area. The change direction of wheat yield in NC after the 2030s, however, is unclear due to large uncertainty in model simulation. The relative change in wheat yield is small and the model agreement on the change direction is generally low in the other regions (i.e. NEC, EC, NWC and XJ). There is a transition to a sustained low yield in SC and a high yield in SWC for wheat, which suggests that climate change would threaten wheat production in SC and benefit wheat production in SWC. The increase or decrease change is inconclusive in the next decade due to large model uncertainty. However, the change direction becomes obvious after the 2030s. The simulated yield in the CC region would increase from the 2000s to 2040s and decrease thereafter. The model agreement on the increase change before the 2040s is high but the agreement on the decrease change after the 2040s is low.

3.4 Climate risk for crop production

Fig. 8 shows the MMs of the relative changes in crop yield with the CO_2 effect at the end of the 21st century. The simulated maize yield would decrease over a large portion of China while it would increase in a relative small area in the high-altitude and cold regions. The largest decrease occurs in the main planting areas in northern and southern China (Fig. 8a). The simulated rice yield would increase over a large portion of China with the largest increase in the high-altitude and cold regions (Fig. 8b). Rice would decrease in some of the current main rice planting areas such as EC and SC. The relative change in soybean yield (Fig. 8c) shows a spatial pattern similar to that of rice yield. The soybean yield would increase in regions outside the traditional agricultural areas but decrease in the main agricultural areas in eastern China. The relative change in wheat yield (Fig. 8d) is negative across China except for a small area in the Tibetan Plateau and NEC. Fig. S1 shows the MMs of the relative changes of the simulated yield of maize, rice, soybean and wheat with the CO_2 effect for the prefectures of China at the end of the 21st century. The maize yield would decrease in most prefectures of SWC, NC and NEC, and would increase in most prefectures of NWC, NEC and SC (Fig. S1a). The yields of rice and soybean would increase in most prefectures in China (Fig. S1b,c). The relative change in wheat yield (Fig. S1d) is negative in China except for some prefectures in SWC, NWC, and EC.

The relative change of the 25th percentiles of maize and wheat yield is negative across China except a small area in the SWC region (Fig. S2). In the worst-case, the yields of rice and soybean would decrease as well across southern and eastern China and the XJ region (Fig. S2). The worst-case assessment shows high risk of production of all types of the main crops and in all the main planting areas. This worst-case shows the upper boundary of the risk assessment given the large uncertainties in the model pairs.

There are large high climate risk areas for maize and wheat yields under a warming climate. The high risk areas for maize yield extend across most agricultural areas in China including NC, SC, XJ, and some parts of NEC and NWC, suggesting a high climate risk for maize production (Fig. 9).

The high risk areas for wheat yield include SC, XJ and a part of EC. The high risk areas for maize and wheat are in the current main agricultural area, indicating that maize and wheat production in China would face great challenge in the future if no further adaptation measures were taken. The high risk area for rice and soybean yields is quite small. The high resilience areas for the 4 crops are generally located in a belt from NEC to SWC which is outside the traditional agricultural area. The prefectures with high resilience of crop yield are mainly located in western and Northeast China (Fig. S3). The prefectures with high risk of crop yield are located in eastern China.

3.5 Model spread and uncertainty

Fig. 10 shows the model spread in the relative change of maize, rice, soybean, and wheat yields across all the available GCM-GGCropM pairs and the model spread induced by GCMs and GGCropMs at the end of the 21st century. The STDs from the crop model ensembles are more than 60% in the Tibet Plateau, suggesting that model uncertainty is large in this region. The model spread for maize is generally less than 40% and the model spread for rice and wheat is generally less than 30% in eastern China. The model spread for soybean and wheat is more than 50% in many parts of eastern China, suggesting that the model uncertainty is especially large for these crop types. The model spread (i.e. STD of the relative change of yield) arising from the GGCropMs is larger than that arising from the GCMs in most parts of China. The uncertainty arising from the GCMs is generally small (less than 20%) in eastern China, while the uncertainty is more than 30% for soybean and wheat over a large area in eastern China.

4. Discussion

There are large discrepancies between the NBSC statistics and the model simulated crop yields in the historical period. The uncertainty of the gridded crop models is still high (i.e. Guo et al., 2010; Tao & Zhang, 2011; Wang et al., 2011; Ye et al., 2013). Moreover, change in water availability (Tang & Lettenmaier, 2012; Schewe et al., 2014; Piontek et al., 2014), which might lead to a cropland conversion from irrigated to rain-fed management or vice versa (Elliott et al., 2014), are not considered in this study. Furthermore, we used the model outputs from ISI-MIP and no further adaptation measures were considered. It is possible that adaptation measures such as changing sowing date and planting area could partially or even totally offset the negative effects of climate change (Yun et al., 2007; Meza et al., 2009; Olmstead et al., 2011). These findings suggest that the inherent model uncertainty is a major issue in assessing climate change impacts on crop yield (Asseng et al., 2013; Rosenzweig et al., 2014). Future assessment of climate change impacts on crop yield should apply further improved models adapted to local settings in China and consider a wide variety of adaptation options.

The simulated crop yields with the CO_2 effects would generally increase in the high-altitude and cold regions in a warming climate. This suggests that climate warming may allow agriculture to move northward or upward into regions which are currently less suitable for crops. The simulated crop yields show mixed patterns of increasing and decreasing changes in the current main agricultural area in eastern China. Climate change is unlikely to benefit maize and wheat productions in the traditional main agricultural area in eastern China but might benefit rice production. These results are in line with previous studies (Xiong et al., 2007) and the IPCC reports (Parry et al., 2007; Field et al., 2014).

The CO_2 fertilization effect would favor crop yields in the future. The simulated crop yields without the CO_2 effect largely decrease while those in the simulations with the CO_2 effect increase. The important role of the CO_2 effect is also discussed in connection with previous results (i.e. Lin et al., 2005; Sakurai et al., 2014). It should be noted that the dominant effects of climate change on crop yield are still inconclusive. The effects of different climatic variables (i.e. temperature, precipitation, radiation, CO_2) on crop yield were assessed in a number of researches (i.e. Tao et al., 2008; Lobell and Gourdji, 2012; Xiong et al., 2012). The dominant variable that affects change in crop yield may vary in different regions. The causes of the climate risk in crop yield should be further investigated in the future.

5. Conclusion

Based on the model projections of 4 GGCropMs, the impact of future climate change on the yields of the major crops (wheat, rice, maize and soybean) in China was assessed. The projections without the CO_2 effect suggest that the yield of maize, rice, soybean and wheat would decrease by up to 25%, while the projections with the CO_2 effect show that the yield would decrease by less than 5% for maize and wheat and increase by 10% for rice and soybean under RCP8.5 at the end of the 21st century in China. With the CO_2 effect, the model results show that the area-weighted yields of rice and soybean in China would increase in the next a few decades with high model agreement. The changes in area-weighted yield of maize and wheat in China are small and the model agreement is low. The response of potential crop yield to climate change shows large regional differences. The uncertainty of relative change in the yields arising from the GGCropMs is approximately twice as large as that arising from GCMs.

The response of crop yield to climate change shows large differences between regions. Climate change would benefit soybean and rice yields in the high-altitude and cold regions which are currently unsuitable for agriculture. Expanding rice and soybean planting areas to NEC and SWC might be a good adaptation option to climate change. The crop yields in the current main grain production area, i.e. the high risk area, would largely decrease in a warming world. Development of new agronomic management strategies may be useful for coping with climate change in these high risk areas. There are large uncertainties among the model projections. Better understanding of the difference between the crop models, which is the major source of the uncertainty, is essential in interpreting the model results.

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Figures:

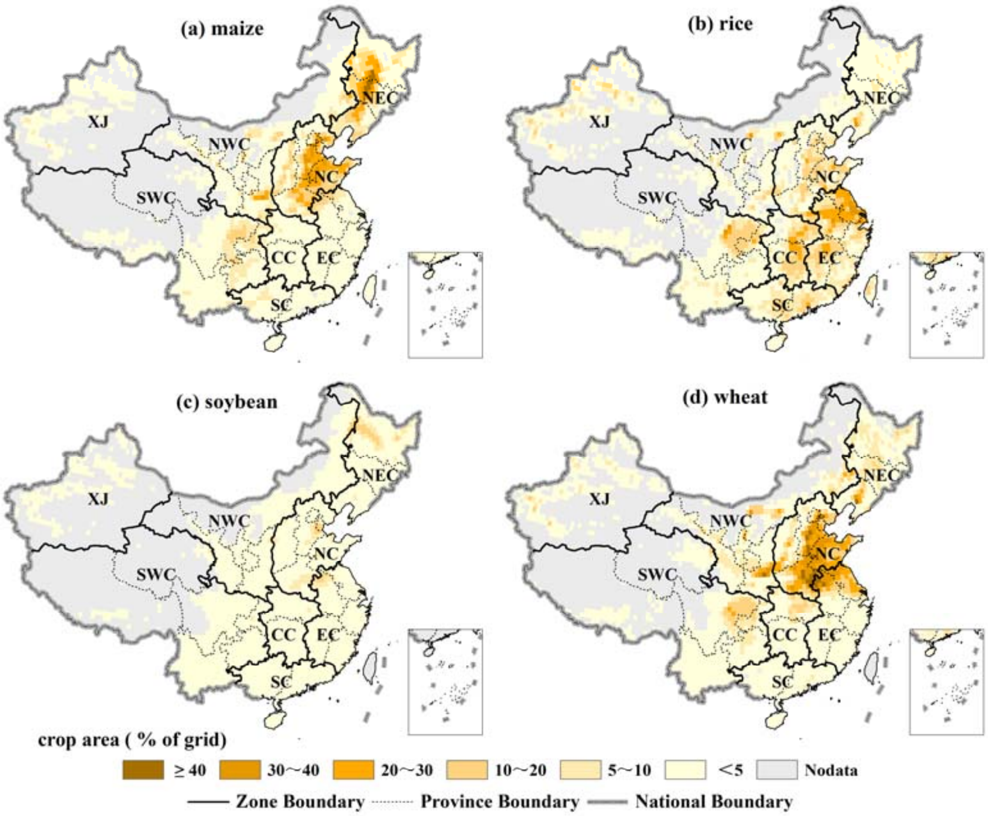

Fig. 1 The 8 regions in China and the crop area (% of grid area) of maize (a), rice (b), soybean (c) and wheat (d). NEC, NC, EC, SC, CC, SWC, NWC and XJ denote Northeast China, North China, Eastern China, South China, Central China, Southwest China, Northwest China and Xinjiang, respectively

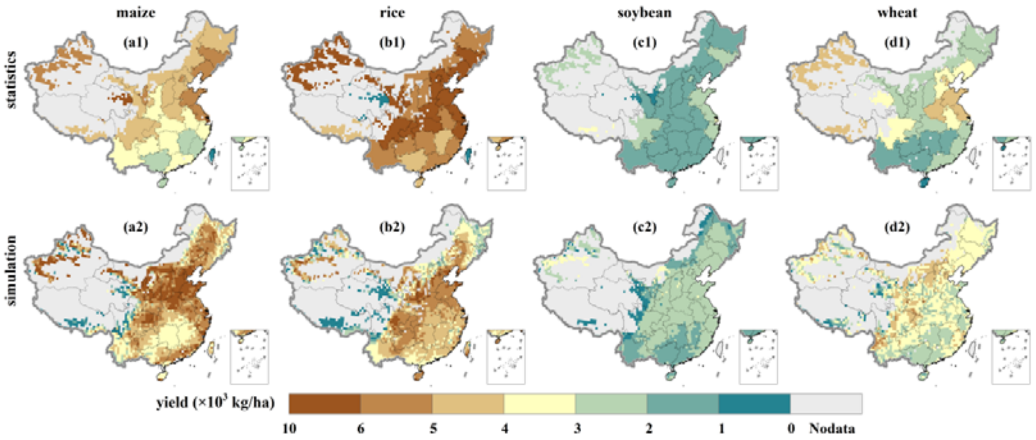

Fig. 2 The MMs of the simulated yields with the CO_2 effect and NBSC reported yields of the 4 major crops in China during 1981-2010. The upper panels are the NBSC yields and lower panels are the simulated yields. The median of the simulated crop yield among the GCM-GGCropM pairs are provided at 0.5-degree grids. The NBSC yields at each province were plotted at the crop area shown in Fig. 1

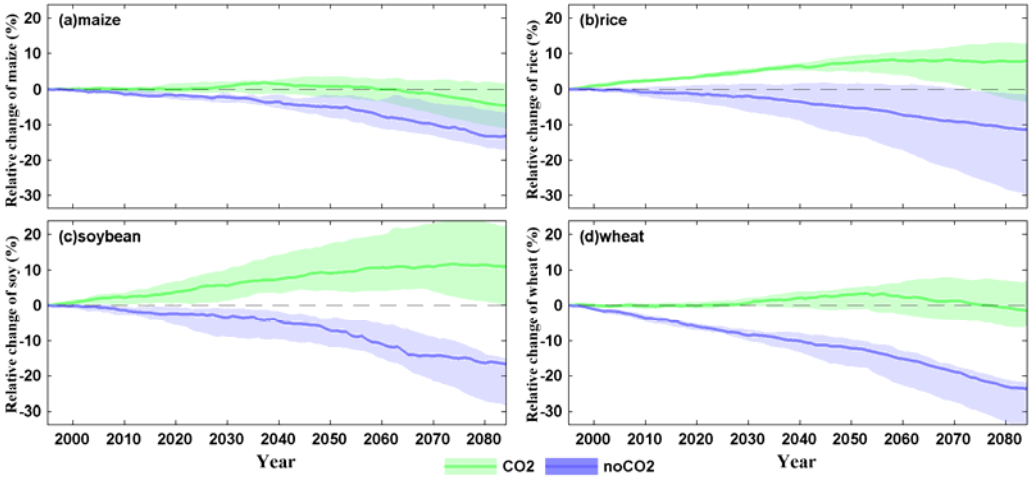

Fig. 3 The relative change of the yield of maize (a), rice (b), soybean (c), and wheat (d) in China under RCP8.5. The blue (green) shade area denotes the inter-quartile range for the simulations with (without) CO_2 effect and the solid line shows the median of the GCM-GGCropM pairs

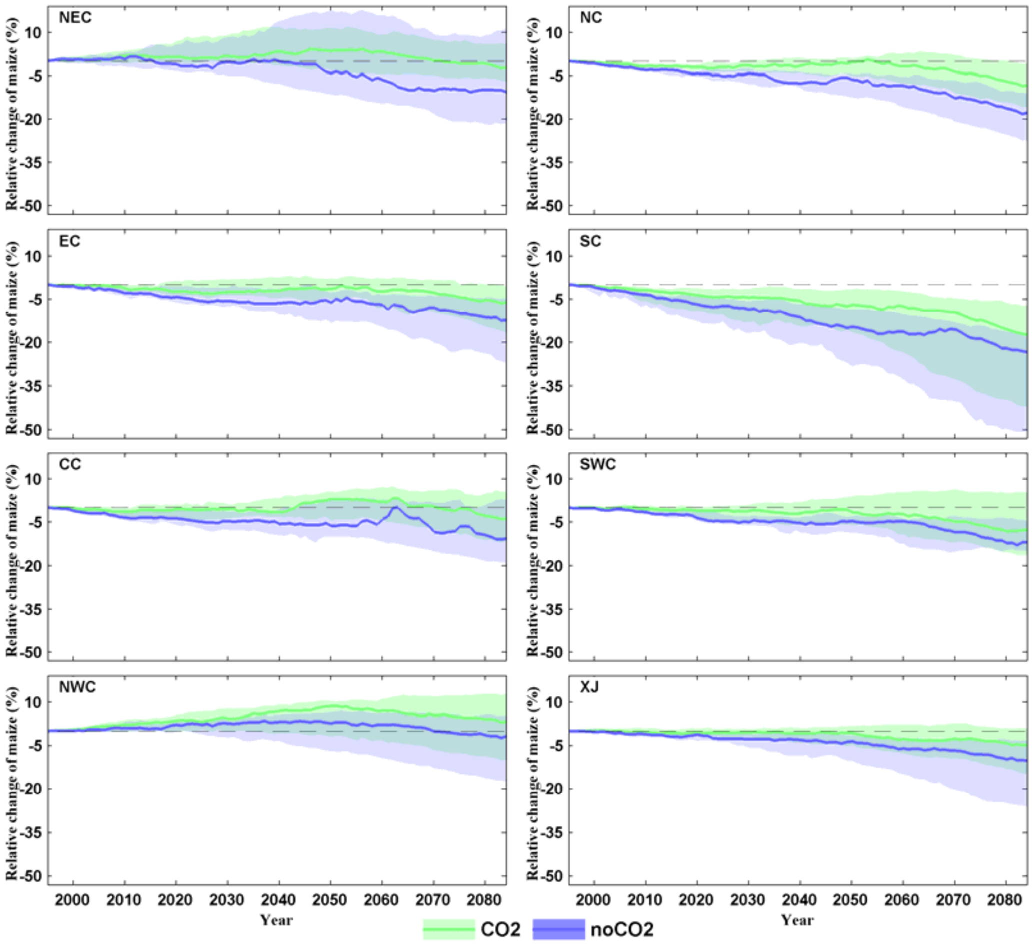

Fig. 4 The relative change of the simulated maize yield in the 8 regions with (without) the CO_2 effect. The MMs and the 25th and 75th percentiles of the model pairs are shown

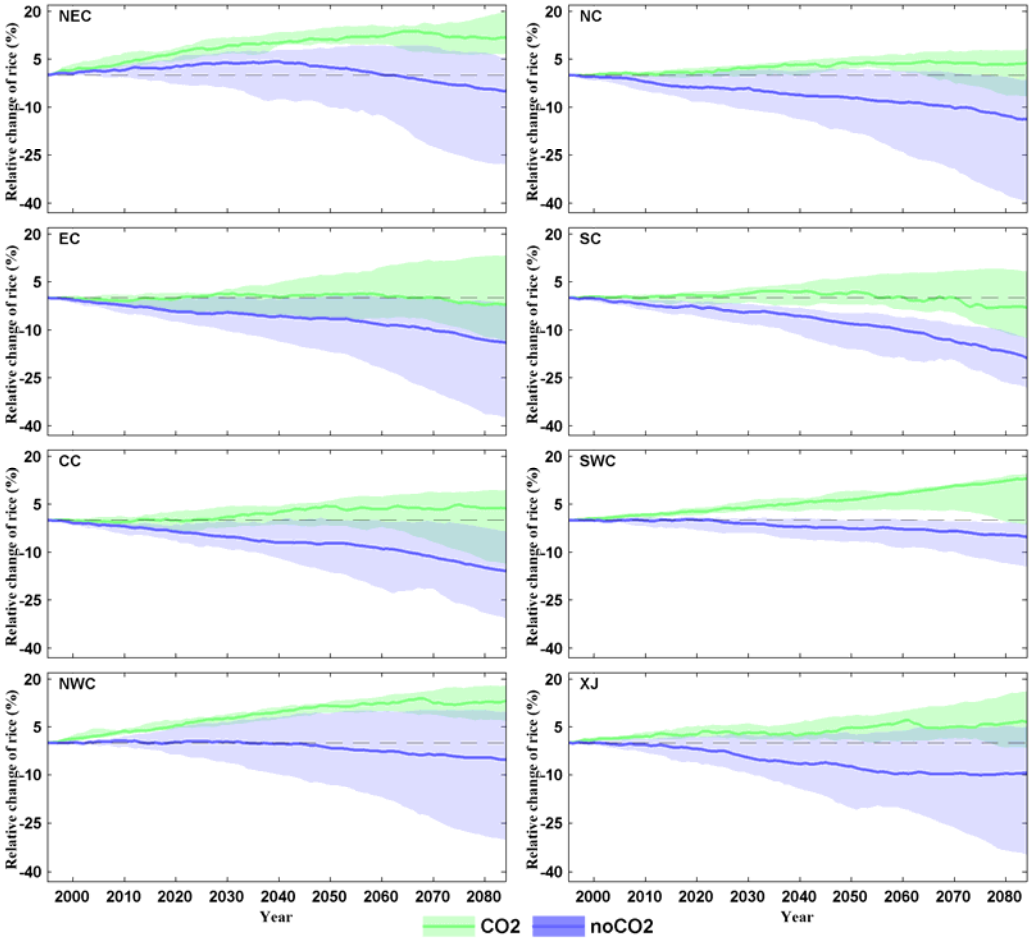

Fig. 5 The relative change of the simulated rice yield in the 8 regions with (without) the CO_2 effect. The MMs and the 25th and 75th percentiles of the model pairs are shown

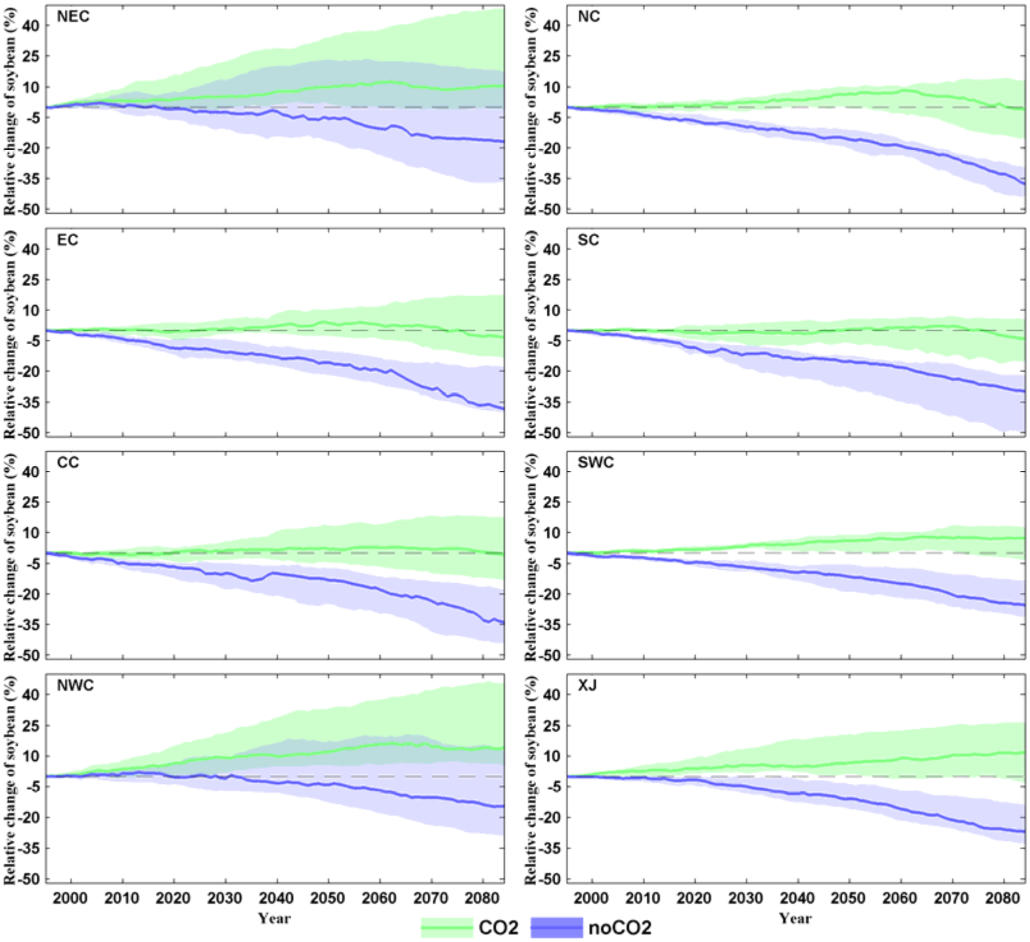

Fig. 6 The relative change of the simulated soybean yield in the 8 regions with (without) the CO_2 effect. The MMs and the 25th and 75th percentiles of the model pairs are shown

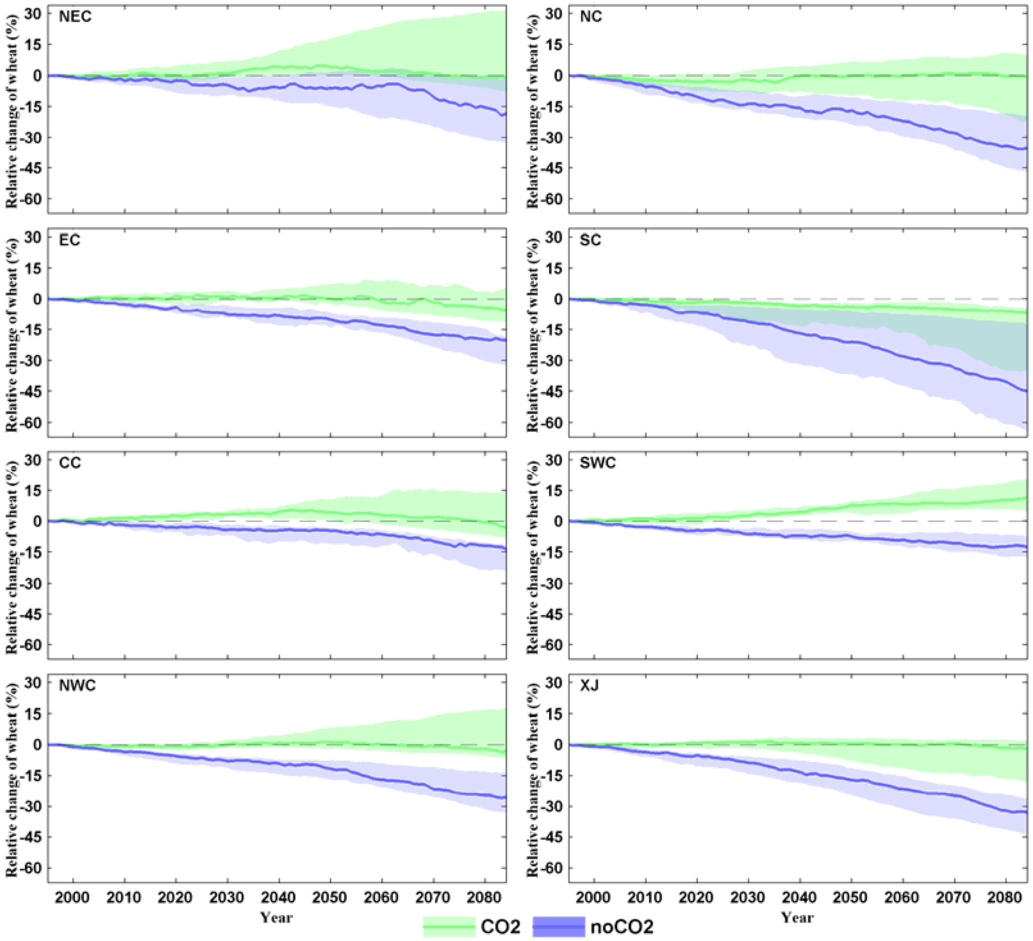

Fig. 7 The relative change of the simulated wheat yield in the 8 regions with (without) the CO_2 effect. The MMs and the 25th and 75th percentiles of the model pairs are shown

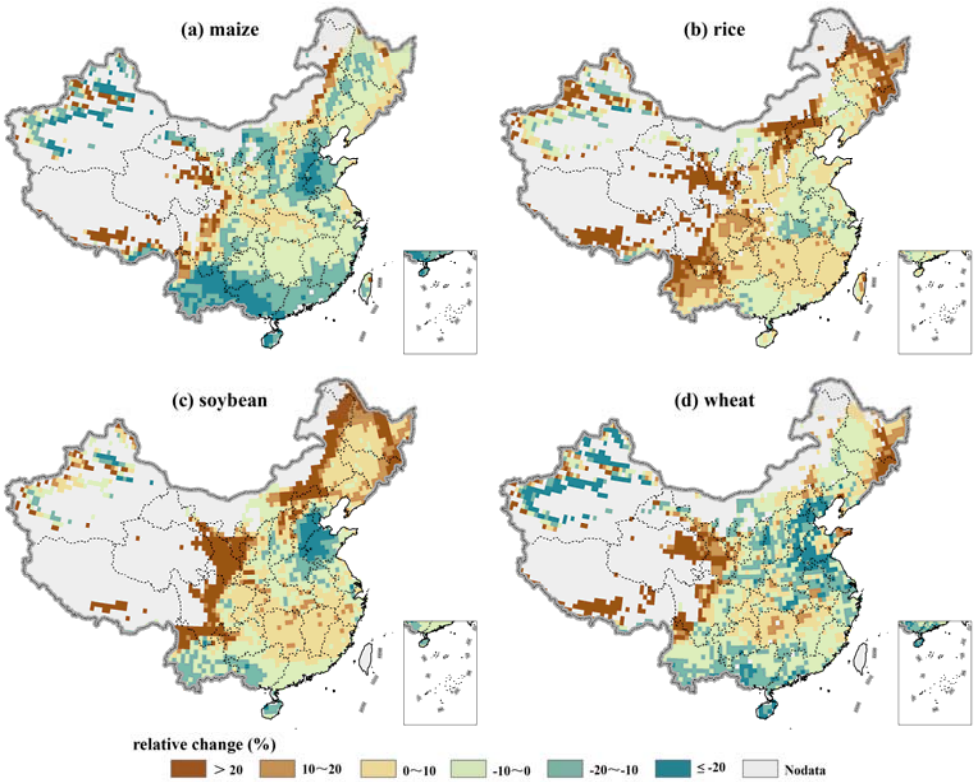

Fig. 8 The MM of the relative change of the simulated yield of maize (a), rice (b), soybean (c), and wheat (d) with the CO_2 effect at the end of the 21st century (2070-2099) comparing with the simulated yield in the historical period (1981-2010)

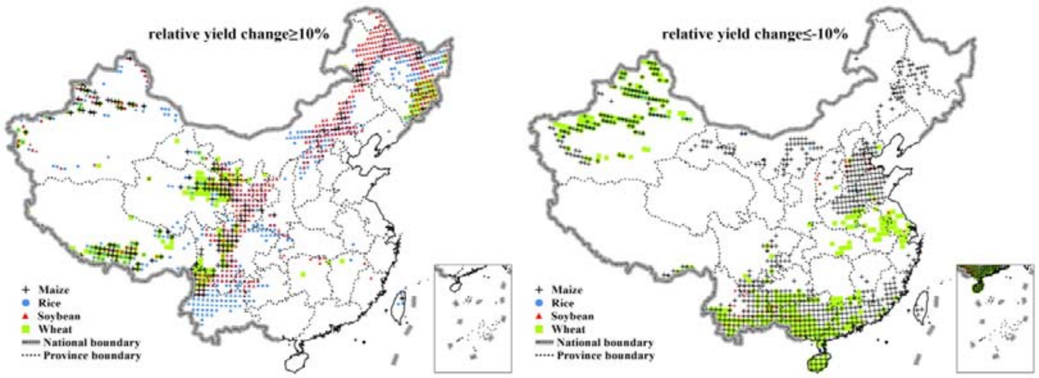

Fig. 9 The high climate resilience areas (left column) and high climate risk areas (right column) for the major crops in China at 0.5 degree grids

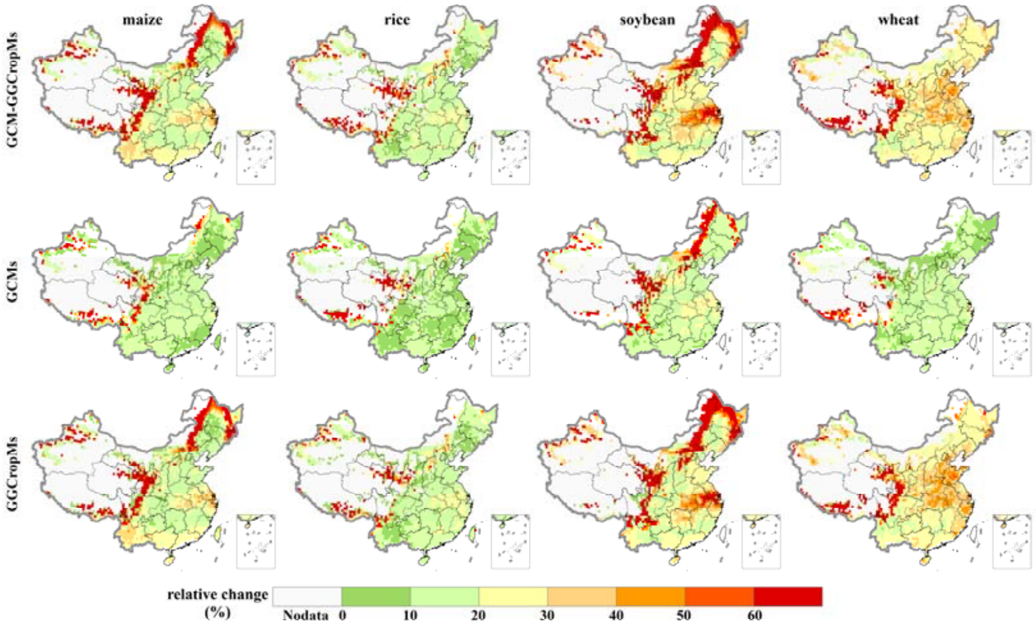

Fig. 10 The model spread of the relative change of the simulated yield of maize, rice, soybean, and wheat with the CO_2 effect at the end of the 21st century (top row) and the model spread induced by GCMs (middle row) and GGCropMs (bottom row)

Tables:

Table 1 Overview of the GCMs and GGCropMs

	Name	Institute	References
GCMs	HadGEM2-ES	Met Office Hadley Centre	Jones et al. (2011)
	IPSL-CM5A-LR	Institute Pierre-Simon Laplace	Mignot et al. (2013)
	MIROC-ESM-CHEM	Japan Agency for Marine-Earth Science and Technology, Atmosphere and Ocean Research Institute (The University of Tokyo), and National Institute for Environmental Studies	Watanabe et al. (2011)
	GFDL-ESM2M	Geophysical Fluid Dynamics Laboratory	John et al. (2012); John et al. (2013)
	NorESM1-M	Norwegian Climate Centre	Bentsen et al. (2013); Iversen et al. (2013)
GGCropMs	EPIC	BOKU, University of Natural Resources and Life Sciences, Vienna	Williams (1995); Izaurralde et al. (2006)
	GEPIC	EAWAG Swiss Federal Institute of Aquatic Science and Technology	Williams et al. (1990); Liu et al. (2007)
	pDSSAT	University of Chicago Computation Institute	Elliott et al. (2013); Jones et al. (2003)
	PEGASUS	Tyndall Centre, University of East Anglia UK/McGill University, Canada	Deryng et al. (2011)

Note: EPIC: short for the Environmental Policy Integrated Climate Model (originally the Erosion Productivity Impact Calculator); GEPIC: short for the Geographic Information System (GIS)-based Environmental Policy Integrated Climate Model; pDSSAT: short for the parallel Decision Support System for Agro-technology Transfer (using the Crop Environment Resource Synthesis (CERES) models for maize, wheat, and rice and the Crop Template approach (CROPGRO) for soybean); PEGASUS: short for the Predicting Ecosystem Goods and Services Using Scenarios model.

Table 2 Simulated and statistical yields in the 8 regions of China in 1981-2010 (kg/hm^2)

Region	Maize		Rice		Soybean		Wheat	
	Simulation	Statistic	Simulation	Statistic	Simulation	Statistic	Simulation	Statistic
NEC	4575	5228	3970	6346	1993	1798	3249	2671
NC	6473	4733	5136	6237	2483	1609	3156	4113
EC	4866	4006	4414	6082	2238	1981	3015	3025
SC	3650	2832	4146	4677	1816	1343	2468	1795
CC	4158	3604	4593	6350	2167	1824	2885	2345
SWC	4162	4016	4094	5484	1827	1827	3560	2866

NWC	5400	4565	4270	6403	1693	1165	3494	2579
XJ	4596	5450	3662	6072	1938	2309	2845	4020

Note: NEC, NC, EC, SC, CC, SWC, NWC and XJ denote Northeast China, North China, Eastern China, South China, Central China, Southwest China, Northwest China and Xinjiang, respectively (see Fig. 1).