Responses to the reviewers

We would like to thank the two reviewers for their thoughtful comments. We have addressed all these comments in our revised manuscript. The point-by-point responses to the comments are provided below.

Reviewer 1:

Some general comments:

- **Question 1**: My major concern is that it is rather a report of finds from readily available and published data and does not provide much added scientific value.

- **Answer**: Thank you for the comment. Although this study used the readily available and published data, it is not a simple illustration of the data. The objective of this study is to identify the high risk areas for crop production under climate change in China and to support adaptation to climate change at regional scale. Although ISI-MIP project has provided the model outputs, these gridded outputs are not readily useful for effective risk reduction and adaptation strategies. The adaptation strategies are usually carried out for different regions and administrative districts. The decision makers are interested in the risk assessment at administrative areas rather than the gridded outputs. Our results provide a starting point for regional studies on vulnerability and adaptation strategies to climate change. It bridges the gap between the modelers and policy-makers. Scientists always hope the model projections could help shape climate adaptation approaches. This study demonstrates an effort at regional scale. We have clarified the objective and scientific significance of this study in the introduction section. We have also added the risk and uncertainty assessments in the administrative districts of the China in order to better support decision making at regional scale (please see Fig.S1 and Fig.S3 in the Supplemental materials).

- **Question 2**: The title may need some adjustment. In the Discussion (P626/L3ff), the authors state that GGCMs show large differences in projected CC impacts and do not reproduce historic yields well. The title should hence include some reference to uncertainties.

- **Answer**: Thanks for the suggestion. We agree that uncertainty is very important in risk assessment and we have revised the title accordingly. We have replaced the title with “A multi-model analysis of change in potential yield of major crops in China under climate change” in the revision.

- **Question 3**: The language could be polished in various places in order to facilitate understanding.

- **Answer**: We have read through the manuscript and polished the language.

- **Question 4**: The Conclusions are rather a summary and need more elaboration.

- **Answer**: We have rewritten the Conclusions section. In the revised section, we have organized the conclusions in two respects: 1) risk of crop productions under climate and uncertainty of the assessment, 2) what could be done in the future. Please see the Conclusion part in the revision.

Some specific comments:

- **Question 5**: P618/L4: "… a couple of global gridded crop models …" why does this not state the number of crop models being used, which is four?

- **Answer**: The crop models used in this study are EPIC, GEPIC, pDSSAT and PEGASUS. We have stated the number of crop models in the revision. It has been replaced with "4 global gridded crop models (GGCropMs)" in the revision.

- **Question 6**: P618/L9: "… show that the potential yields of rice may increase over …" should be "… show that the yields of rice may potentially increase over …" to make clear that not yield potential is meant.

- **Answer**: We have corrected it following the suggestion.

- **Question 7**: P618/L11: should be "which" instead of "where".

- **Answer**: We have replaced "where" with "which".

- **Question 8**: P618/ L11: should say "yields" instead of "production". Production is not necessarily impacted by CC, as it also depends on the harvested area, agronomic inputs, etc.

- **Answer**: Corrected. We have checked the use of 'yield' and 'production' throughout the manuscript.

- **Question 9**: P621/L2: "harvesting time" should be "number of cropping seasons".

- **Answer**: Revised.

- **Question 10**: P621/L15: There actually is partial adjustment in some models: GEPIC takes adaption into account in terms of decadal adjustment of planting and harvest dates and the distribution of spring and winter wheat. PEGASUS and LPJ-GUESS adjust the GDD of their cultivars. You may need to check more carefully the descriptions of models that produced the data.

- **Answer**: We have revised the descriptions and made the statements more accurate. The sentence “All the GGCMs have taken into account the CO_2 fertilization effects and assumed no adaptation, i.e. the crop planting area and irrigation area do not change in the future.” should be “All GGCropMs considered two scenarios: All GGCropMs run with two experiments: one takes into account the CO_2 fertilization effects but the other one does not.”

- **Question 11**: P622/L7: “moving average”: what kind of average?

- **Answer**: In order to remove inter-annual variability of yield, we used 30-year moving average of the data. We have replaced “moving average” with “30-year moving average” in the revision.

- **Question 12**: P623/L16: “This is likely due to the limitations of rice model in the GGCMs”. How do you derive this conclusion? Apparently, also the other crops are not represented too well in the GGCMs in terms of reproducing historic reported yields. Besides actual crop growth algorithms, the global crop models also use different input data (e.g. soils, planting dates, growing season lengths) and various management assumptions. I’m not sure whether any conclusions on model performance in terms of bio-physical processes can be drawn from the ISI-MIP crop model outputs.

- **Answer**: Thanks for the insightful suggestion. We agree that no conclusions on performance of bio-physical processes in the models may be drawn from ISI-MIP outputs. We have rewritten the related discussions.

- **Question 13**: 626/L11: See comment on adaptation above.

- **Answer**: We have rewritten the sentence in the revision: “Furthermore, some GGCropMs assumed none adaptation to climate change.”

- **Question 14**: P627/L8: The conclusions should draw new findings or provide an outlook on what further research or policy decisions, etc. may be needed in the future based on what has been presented and discussed in the foregoing sections. This Conclusions chapter however is rather a summary that has already been provided in the abstract.

- **Answer**: Thanks for the suggestion. We have rewritten the conclusion section following the suggestion. Please see the answer to Question 4.

- **Question 15**: P628/L10: various names in the references have been misspelled (e.g. Challiore, Izauurade, Lobel). The authors for “Future scenarios of European agricultural land use …” are not correct. The authors should check all references carefully and correct them where necessary.

- **Answer**: We have checked the references throughout the manuscripts and corrected the misspells. Some modifications are shown as follows:

L1150: “Challiore” has been changed to “Challinor”

L1166 “Khabarow” has beenchanged to “Khabarov”

L1170: “Glotter, M.” has beenchanged to “Kelly, D.”

L1172: “Elliott, J. Glotter, M., Best, N., Wilde, M., Glotter, M., and Foster, I.” has been changed to “Ewert, F., Rounsevell, M. D. A., Renginster, I., Metzger, M. J., Leemans, R.”

L1206: “Izauurade” has been changed to “Izaurralde”

L1238: “Lobel, D. B.” has been changed to “Lobell, D. B.”

L1329: “Kin” has been changed to “Kim”

L1374: have deleted “Rodomiro, O. ……, 2008.”

L1355: “W arszawski” has been changed to “Warszawski”

L1437: “Yolozawa” has been changed to “Yokozawa”

L1441: “Tornton” has been changed to “Thornton”

L1446: “Wahaa” has been changed to “Waha”

L1453: “Pontek, F.” has been changed to “Huber, V.”

L1454: “Research Design of the Inter-Sectoral Impact Model Intercomparison Projection (ISI-MIP)” has been changed to “The Inter-Sectoral Impact Model Intercomparison Projection (ISI-MIP): project framework”

L1472: have deleted “Xiong, W., Balkovic, J., ….., 2014.”

L1544: “Yand” has been changed to “Yang”

- **Question 16**: References: Xiong, W. et al. (2012) Untangling relative contributions of recent climate and CO_2 trends to national cereal production in China. Environ. Res. Lett. 7 044014

- **Answer**: It is a closely related reference and we have added it in the Discussion in the revision.

Reviewer 2:

Some general comments:

- **Question 1**: The paper is a valuable, relevant and interesting contribution to the literature, however it presently merely reports the regional findings rather than discussing them in the context of existing knowledge or investigating the underlying causes of changes observed. Therefore to me it fails to clearly identify whether anything new was learned.

- **Answer**: Thank you for the comment. The objective of this study is to identify the high risk areas for crop production under climate change in China and to support adaptation to climate change at regional scale. Although the gridded outputs were provided by the ISI-MIP project, the decision makers are usually not well informed from the scientific results. Our results could show the risk assessments at the administrative zones (please see Fig.S1 and Fig.S3 in the Supplemental materials) and thus provide a starting point for regional studies on vulnerability and adaptation strategies to climate change. It bridges the gap between the modelers and policy-makers. We have clarified the objective and scientific significance of this study in the introduction section. Furthermore, we have enhanced the discussion on the underlying causes of the risk in the revision.

- **Question 2**: The paper would benefit from discussing the main climatic causes of the changes observed by comparing patterns in the changes in temperature, precipitation and CO_2 to the patterns observed in crop yields. I realize that it would go beyond the scope of this paper to do an in-depth analysis here, but it is not satisfying to not receive any information about how climate changes in different GCM projections. Do the crops that increase growth mainly benefit from CO_2 fertilization? Do the crops that show a decline of yields mainly suffer from increased water stress?

- **Answer**: As the reviewer kindly mentioned, an in-depth analysis of the causes is beyond the scope of the paper. We have added some additional analyses in order to better understand the causes of the changes of relative yields. More specifically, we have investigated the role of CO_2 fertilization in the risk assessments. Please see "3.3 Projected changes in crop yield" (Fig.3 to Fig.7).

- **Question 3**: I think it would be valuable to receive information from your analysis about leading reason for the grey areas of inter-model uncertainty behind the temporal plots of median crops yields. Are they mainly due to differences between the crop models, mainly due to differences between the GCMs, or a mix of both, and if so, in what relation?

- **Answer**: In the revision, the model spread was analyzed to understand the uncertainty of the assessment. The standard deviation from all the available GCM-GGCM pairs was used to quantify the model agreement. The model spread caused by GGCMs and GCMs was separately evaluated. The standard deviation of the estimates from the GGCMs was firstly calculated for each GCM. The averaged GGCM standard deviations of the GCMs was then used to assess the model spread caused by GGCMs. Using the same calculation procedure, the model spread caused by GCMs was estimated and compared with the model spread caused by GGCMs. We have added the method in “2. Materials and methods”, and the results in “3.5 Model spread and uncertainty” (please see Fig.10).

- **Question 4**: You announce at the end of the introduction that you intend to compare your results to those obtained from AR4-based studies but as far as I can detect, do not do so subsequently. More generally: the strength of your study is that it is multi-model, multi-GCM using AR5 scenarios. The important question left open by your paper is: what do we learn from such a multi-GCM, multi-GGCM AR5 analysis? Do the results simply confirm previous knowledge (if so, in what way is that significant? Were there doubts about earlier studies?) or add to it? I suggest that you more systematically discuss your results (a) with respect to the present state of knowledge about climate impacts on crops in China, identifying the advances made (even if it is an important confirmation of existing knowledge), (b) with respect to AR4 in particular (if that is important – you mention it in the introduction), (c) with respect to single model studies. In summary: what is the advance in knowledge you provide?

- **Answer**: Thanks for the suggestions. We have provided more systematically discussions in the discussion section. As the previous AR4 studies are under different climatic scenarios, we compared the differences between AR4 and AR5 assessments qualitatively. We have modified the statements in the introduction accordingly.

- **Question 5**: You discuss the median behavior a lot, and the disagreement between model pairs. However, would not the “worst case” be of particular importance, too? If the best case happens, no problem. The median case is of interest. But the worst case could potentially really be a problem. It could be the real case. Maybe those models are right. So it is not just uncertainty, it is also a case where “the worst case cannot be excluded scientifically and is therefore a non-zero likelihood, i.e. a risk”. So I suggest you also discuss the worst cases as such.

- **Answer**: We agree the worst case is meaningful for risk assessment. We have shown a figure of the worst case and have added a brief discussion regarding the risk of the ‘worst case’ (please see Fig.S2 in the Supplemental materials).

Some other, more minor comments:

- **Question 6**: I suggest to not use the abbreviation GGCM (global gridded crop model) because it is so similar to GCM. It can cause mistakes and confusion.

- **Answer**: We have replaced “GGCM (global gridded crop model)” with “GGCropM (global gridded crop model)” throughout the manuscript.

- **Question 7**: The crop models used are established models described elsewhere, but the paper should very briefly describe what they do and what not.

- **Answer**: We have added a very briefly description about the crop models in the second paragraph of “2. Materials and methods” in the revision. The description is shown below.

The simulated crop yield data were taken from 4 GGCropMs (EPIC, GEPIC, pDSSAT and PEGASUS) (see table 1). These models may have different model types and different parameterizations of soil and crop processes. The dissimilarities of the models and the consequent caution needed in interpreting the model results are discussed in Rosenzweig et al. (2014).

- **Question 8**: Figures 6 and 7 are never mentioned in the text. You discuss Figs. 4 and 5, but not 6 and 7.

- **Answer**: It was corrected in the revision. Please see the fourth paragraph and fifth paragraph in “3.3 Projected changes in crop yield” in the revision.

- **Question 9**: How do results compare to discussions in the IPCC’s AR5 WG2 report?

- **Answer**: Although our results are generally in line with the large pattern shown in the IPCC’s AR5 WG2, our results have provided the risk assessment in details for different administrative zones. We have added a brief discussion in the revision.

- **Question 10**: The English is ok; however, there are quite a number of small but important language mistakes that are typical for non-native speakers. Often it is about the word “the”, so let me explain once more, since it occurs many times: you use “the” before a noun when you mean a specific thing or group of things, one that you identify: you are talking about those things (for example: the coast of China, the GGCMs used). You do not use “the” if you are talking about a type of thing generally without a specific thing referred to (for example: “GGCMs simulate climate”). There are too many small language problems for me to list, so let me just do it for the abstract so you get an idea: (i) “a couple of” usually means: two. You mean: “a number of” (since there are 4). By the way: why not just say “four GGCMs”; (ii) “may benefit food production IN (not over)”; (iii) “where are outside”; you mean “which (or that) are outside”; (iv) “such as North China Plain” should be “such as the North China Plain”; (v) “new agronomic strategy”; better “nee agronomic strategies” or “a new agronomic strategy”.

- **Answer**: Thanks for the comments. We have read through the manuscript and polished the language.

A multi-model analysis~~Impacts~~ of change in potential yield~~Future Climate Change on Potential Yields~~ of major crops~~Major Crops~~ in China under climate change

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

~~Institute of Geographic Sciences and Natural Resources Research, Chinese Academy of Sciences, Beijing 100101, China~~

~~Correspondence to: Q. H. Tang (tangqh@igsnrr.ac.cn)~~

Abstract: Climate change may affect crop growth~~development~~ and yield, which~~and~~ consequently casts a shadow of doubt over China's food self-sufficiency efforts. In this study, we used the ~~model~~ projections derived from 4~~of a couple of~~ global gridded crop models (GGCropMs)~~(GGCMs)~~ to assess the effects of future climate change on the ~~potential~~ yields of the major crops (i.e. wheat, rice, maize and soybean) in~~over~~ China. The GGCropMs~~GGCMs~~ 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 ~~may~~ 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~~over a large portion~~ of China. Climate may benefit rice and soybean yields in ~~food productions over the~~ high-altitude and cold regions which~~where~~ are not in~~outside~~ current main agricultural area. However, the potential yields of maize, soybean and wheat may decrease at~~in a large portion of~~ the major food production area.~~current main crop planting areas such as North China Plain.~~ Development of new agronomic management strategies~~strategy~~ 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~~The linear trend of globally averaged combined land and ocean~~ surface temperature has increased by ~~is~~ 0.85 ~~(0.68 to 1.06)~~ °C/100 yr~~,~~ over the period of 1880-2012, and it is likely to increase 1.5-2 °C at the end of 21st century compared ~~1880–2012 (IPCC, 2013). According~~ to the period of 1850-1900~~assessment in the Fifth Assessment Report of the Intergovernmental Panel on Climate Change (IPCC AR5), global surface temperature change at the end of the 21st century (relative to 1850–1900) is likely to exceed 1.5 °C in all but the lowest model scenario considered, and likely to exceed 2 °C for the two high scenarios~~ (IPCC, 2013). In China, air temperature has

Y. Yin
Key Laboratory of Water Cycle and Related Land Surface Processes, Institute of Geographic Sciences and Natural Resources Research, Chinese Academy of Sciences, Beijing 100101, China

Q. Tang (✉)
Key Laboratory of Water Cycle and Related Land Surface Processes, Institute of Geographic Sciences and Natural Resources Research, Chinese Academy of Sciences, Beijing 100101, China
Email: tangqh@igsnrr.ac.cn

X. Liu
Key Laboratory of Water Cycle and Related Land Surface Processes, Institute of Geographic Sciences and Natural Resources Research, Chinese Academy of Sciences, Beijing 100101, China

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increased by 0.5-0.8~~0.5~0.8~~ °C during the past 100 years (Qin et al., 2005; Ren et al., 2005a; Ren et al., 2005b). In the end of 21st century, surface~~The nationwide air~~ temperature increases will exceed ~~would increase by 1.3~~~2 °C ~~1 °C in 2020, 2.3~3.3 °C in 2050, and 3.9~6.0 °C in 2100 as compared~~ with a probability of over 60% in all regions of China (Yang et al., 2014). ~~ir temperature in 1961~1990 based on the model projections provided by China Meteorology Administration (CMA) (Qin, 2007). The warming magnitude would increase from south to north. Particularly, significant temperature rise is projected in northwestern and northeastern China (Ren et al., 2005b; Qin, 2007).~~

The impacts of climate change on crop yields and food production have prompted concern worldwide. There are numerous~~large numbers of~~ studies devoted to assessing the impacts of climate change on agriculture production ~~variation~~ over the past ~~few~~ decades (Nicholls, 1997; Lobell et al., 2007; Tao et al., 2008b;~~2008;~~ Joshi et al., 2011) and ~~the potential impacts of~~ future ~~climate change on agriculture production~~ (Jones et al., 2003; Ewert et al., 2005; Lin et al., 2005; Tao et al., 2008a;~~2008;~~ Thornton et al., 2009; Liu et al., 2013b). The projections ~~2013). A lot~~ of changes~~studies had been carried out to project the change~~ in crop yields in China are widely reported using crop models (process-based or statistical) with GCM outputs which were generated for the ~~Fourth~~ Assessment Report of IPCC (i.e. Parry et al., 2004; Tao et al., 2008a;~~2008;~~ 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~~A few studies suggested~~ that the production of major food crops in China might increase under various emission scenarios ~~generated for IPCC AR4 (Liu et. al., 2013)~~ 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~~s are~~ important for developing adaptation and mitigation measures in agricultural regions of ~~sector to climate change for~~ China. However, most existing assessments have been~~were~~ made based on a single crop model forced by climate change experiments generated for IPCC AR4. In addition, only a ~~and~~ 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~~reaches~~ 52 million tons~~tones~~ 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~~, The Inter-Sectoral Impact Model Intercomparison Project (ISI-MIP)~~ is a community-driven modeling effort with the goal of providing cross-sectoral global impact

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assessments based on the newly developed climate scenarios (Warszawski et al., 2014) ~~2013).~~ It provides an opportunity for assessing agricultural risks of climate change in the 21st century using the ~~Representative Concentration Pathways (~~RCPs~~)~~ for IPCC AR5 (Rosenzweig et al., 2014;~~2013;~~ Elliott et al., 2014)~~2013).~~ The main objective of~~GGCMs were forced with the bias-corrected climatic variables from RCP 8.5 outputs of 5 global climate models (GCMs). In~~ this study is~~, we used the model projections of a couple of GGCMs in ISI-MIP~~ to assess the effects of future climate change on the potential yields of the major corps ~~crops~~ (i.e. wheat, rice, maize and soybean) using the model outputs of 4 GGCropMs (i.e. EPIC, GEPIC, pDSSAT and PEGASUS) in ISI-MIP~~, over China implied by the IPCC AR5 climate change experiments.~~ The model projected yield changes of the crops are illustrated at administrative area level and the uncertainty of model projections is~~was~~ analyzed. ~~The agricultural risks of climate change in China were demonstrated and discussions have been made by comparing the assessments using IPCC AR5 and AR4 climate change scenarios when the corresponding assessments using AR4 scenarios were available in the literature.~~

2. Materials and methods

The ~~agricultural land and irrigated area data were obtained from MIRCA2000, the~~ global ~~monthly~~ 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 ~~s around the year 2000 (Portmann et al., 2010). The~~ MIRCA2000 data consist of all major food crops including wheat, rice, maize and soybean (Portmann et al., 2010). The data set refers to the period of 1998-2002~~1998~2002~~ and has been made available with a spatial resolution of 0.5°×~~-degree by~~ 0.5°~~-degree~~ by ISI-MIP (Warszawski et al., 2014)~~2013).~~ The annual crop yields statistics from ~~of the four crops in~~ 1981 to ~~-~~2010 were provided for each province of China by NBSC ~~the National Bureau of Statistics of China~~ (http://www.stats.gov.cn/). There~~, annual harvesting time~~ is one cropping season of a year in most of ~~1 in the~~ northern China and 2~~, or~~ 3 seasons in ~~the~~ southern China. The current GGCropMs cannot~~GGCMs can't~~ simulate well the multiple harvestings of rice (i.e.~~(e.g.~~ Priya et al., 2001; Xiong et al., 2014). For simplicity, we~~We~~ used the yield in a single harvesting time, although there are three~~i.e. early season, mid-season, or single cropping late rice yield of the~~ different rice planting systems: single cropping rice, double cropping rice, and triple cropping rice in China (Mei et al., 1988). The yield in the single harvesting time was compared with the simulated potential rice yield of GGCropMs.~~GGCMs.~~

The simulated ~~potential~~ crop yield data were taken from ~~the simulations of~~ 4 GGCropMs (~~GGCMs -~~EPIC~~, (Williams, 1995; Izaurralde et al., 2006)~~, GEPIC~~, (Williams et al., 1990; Liu et al., 2007),~~ pDSSAT ~~(Jones et al., 2003; Elliott et al., 2013)~~ and PEGASUS) (see Table 1). These models may have different 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). ~~(Deryng et al., 2011).~~ The GGCropMs~~GGCMs~~ were forced with the bias-corrected climatic data (Hempel et al., 2013) for the historical period 1971-2005~~(1971~2005~~ (except EPIC ~~of~~ which was for~~it is~~ 1980-2010)~~1980~2010)~~ and the RCP 8.5 for future climate scenario 2006-2099~~(2006~2099~~ (except EPIC ~~of~~ which was for~~it is~~ 2011-2099) ~~2011~2099) climate scenario~~ of 5 GCMs from the Fifth Coupled Model Intercomparison Project (CMIP5) (Taylor et al., 2012). All GGCropMs run with two experiments: one takes~~the GGCMs have taken~~ into account the CO_2 fertilization effects and the other does~~assumed no adaptation, i.e. the crop planting area and irrigation area do~~ not~~, change in the~~

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~~future.~~ In order to assess the performance of GGCropMs,~~GGCMs,~~ the GGCropMs~~GGCMs~~ simulations with the CO_2 fertilization effect in the historical period were compared with the yield statistics from NBSC.~~statistical yields.~~ Table 1 shows an overview of the 5 GCMs and 4 GGCropMs.~~GGCMs.~~ All the 4 GGCropMs~~GGCMs~~ provided the 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 in irrigated and rain-fed cropland. ~~For more detailed descriptions of the main characteristics of the GGCMs, the readers are referred to Rosenzweig et al. (2013). The GGCMs provide crop yield simulations in irrigated and rain-fed agriculture. Since irrigation practice reduces water stress, the simulated crop yields in the irrigated agriculture are usually larger than that in the rain-fed agriculture.~~

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 the administrative boundary (Fig. 1)~~Fig. 1)~~. The average crop yield of~~over~~ 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~~GCM-GGCM~~ pair. There are ~~5 GCMs and 4 GGCMs, making a total of~~ 20 model pairs (5GCMs×4GGCropMs) for maize, wheat and soybean. Meanwhile, there are 15 GCM-GGCropM~~GCM-GGCM~~ pairs for rice because the rice yield is missing in PEGASUS simulations. The 30-year moving averages of the crop yield ~~time series~~ from 1981-2099~~1981–2099~~ were computed. The first 30-year moving average value was for the period of 1981-2010~~1981–2010~~ (denoted as 1995, the center year of the period). The ~~, and the other moving average years were also denoted as the~~ center year of the 30-year moving average was used to denote the 30-year period.~~,~~ The relative ~~crop~~ yield change was computed as the crop yield difference between a 30-~~the moving average~~ year period in future and ~~1995 (i.e.~~ the historical period of 1981-2010 ~~1981–2010),~~ divided by the ~~crop~~ yield in the historical period. We computed the multimodel-ensemble medians (MMs) of the relative ~~crop~~ yield change from all the available GCM-GGCropM~~GCM-GGCM~~ pairs, together with~~pairs. We showed~~ the inter-quartile~~interquartile~~ range (the value of the 75th percentile minus that of the 25th percentile) of the ~~of the~~ multimodel ensembles.

The MMs of ~~, to quantify the uncertainty of the model projections. If MM value of the~~ relative ~~crop~~ yield change with the CO_2 effect were calculated at the gridded outputs and 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~~(2070–2099)~~ 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

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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 ~~crop area~~ of maize, rice, soybean and wheat in China. The maize planting area is mainly distributed in the Northeast China (NEC), North China (NC) and Southwest China (SWC). The rice planting area spreads across the eastern China with large area in the East China (EC), ~~Central China (CC),~~ South China (SC), NC and Central China (CC), and~~,~~ parts of the Northeast China (NEC), Xinjiang (XJ) and Sichuan Province~~province~~ in the SWC. The planting area of soybean is relative small compared~~comparing~~ with ~~the areas of~~ maize, rice and~~or~~ wheat. The main planting area ~~of soybean~~ locates in the NEC and NC. The wheat planting area is mainly ~~distributed~~ in the NC, northern EC, parts of the NEC and Sichuan Province~~province~~ in the SWC.

3.2 Simulated and NBSC statistical yields in 1981-2010~~1981~2010~~

Fig. 2~~Fig. 2~~ shows the simulated and NBSC statistical yields in~~of~~ China during 1981-2010~~,1981~2010.~~ The NBSC yields were reported at each province~~, and the crop yield simulations were provided at 0.5 degree grids.~~ Apparently, the simulated patterns demonstrate that~~preserve~~ local details inside~~side~~ each province while ~~the~~ 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 at the main maize planting areas, such as the NEC, NC, and NWC~~Northwest China (NWC)~~ and are relatively low at the CC and SC (Fig. 2 a1,a2)~~.a,b).~~ It seems that GGCropMs~~the GGCMs~~ overestimate ~~the~~ maize yields in the most areas of China, but underestimate ~~the~~ 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)~~.c,d). This is likely due to the limitation of rice model in the GGCMs (Xiong et al., 2014).~~ In the EC~~eastern China,~~ both simulation and NBSC data show high rice yield in a belt from the southern NC to Sichuan Province~~province~~ in the SWC, and low rice yield in the northern~~most~~ and southern provinces. In the western China, GGCropMs~~the GGCMs~~ simulation suggests lower rice yield in the high-altitude and cold regions than ~~in~~ the low-altitude areas. The NBSC data show low rice yield at the high-altitude region such as 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)~~.e,f).~~ In the main ~~soybean~~ planting areas of soybean in the 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)~~.g,h).~~ The NBSC wheat yield is high in the main ~~wheat~~ planting area such as the NC, parts~~and part~~ of the NWC and XJ, but it~~and~~ is low in the southern China. The simulated wheat yield shows some high values in the ~~a mixed pattern with higher yield in a~~ belt from the NWC to Sichuan Province~~.province in SWC.~~ Although, the model simulations are~~is~~ imperfect in terms of its ability to reproduce the NBSC statistical yield, they can ~~state-of-art model can simulate the order of the crop yields and~~ capture the difference among the crops. The comparison between model simulation and NBSC yield~~statistics~~ illustrates the inherent uncertainty of the state-of-art GGCropMs~~.GGCMs.~~ Due to the large discrepancy between ~~the model~~ simulated yield and NBSC statistical yield~~statistics~~ in the historical period, the relative changes, rather than the absolute differences, are analyzed for future changes in crop yields.

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3.3 Projected ~~temporal evolution of~~ changes in crop yields

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 largest by about 25% at the end ~~for the period~~ of 21st century. With CO_2 effect, the ~~1995–2085. 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 the previous studies (i.e. ~~(e.g.~~ 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 ~~25th and 75th percentile envelope~~ of maize yields covering ~~covers~~ the zero change line throughout the study period indicates ~~, indicating~~ that the model agreement ~~consensus~~ on the change direction is low. ~~does not exist.~~ The simulated maize yield decreases by 3.3% in the late 21st century although the model uncertainty is high (Fig. 3a). There ~~In the ensemble median, there~~ is a ~~transition to a~~ sustained high~~er~~ yield for rice and soybean beginning ~~that begins~~ 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 ~~suggesting~~ climate change may benefit rice production in the next ~~a~~ few decades. The MMs ~~median~~ of the simulated rice yield keeps 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 ~~in~~ the 2040s to 2060s, and slightly ~~2050s, and slight~~ decrease after the 2060s ~~2050s~~ (Fig. 3d). The relative change in wheat yield is generally small (between -5% and ~~(~~<5%) and the agreement of the model pairs in ~~on~~ the change direction is low.

Fig. 4 ~~Fig. 4~~ shows the relative changes in maize yield at the 8 ~~eight~~ regions of China. Without ~~The median of~~ 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 increases ~~increases~~ slightly before the 2060s and decrease~~s~~ slightly thereafter in the main maize planting region NWC ~~area NEC~~. However, there is no model consensus on the change trend ~~direction~~ throughout the study period. In the NC, another main maize planting area ~~, NC,~~ the simulated maize yield would decrease ~~decreases~~ slightly with high model agreement before the 2030s, which suggests ~~suggesting~~ that maize production in the NC may decrease in the next ~~a~~ few decades. The simulated maize yield would decrease largely after the 2050s although the model agreement on the decrease is low. In the 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 the NWC would increase by 5% before the 2030s. The maize yield after the 2030s would keep the high level after the 2030s in the NWC although the model agreement becomes low. The simulated maize yields in the EC, CC, XJ ~~SWC~~ and SWC ~~XJ~~ show a general decrease~~ly decreasing~~ change with ~~but the model agreements on the change direction are~~ low model agreements.

Fig. 5 shows the relative changes in rice yield at the 8 ~~eight~~ 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 keep increase. ~~The simulated rice yield shows generally increasing trend~~ with high model agreement in the ~~northern and western China (i.e. NEC, NC,~~

NWC, SWC ~~, and~~ XJ and NEC ~~)~~. The simulated rice yield would increase by about 5% in the NC and XJ and ~~increase~~ by more than 10% in the SWC, NEC and NWC at the end of the 21st century. In the ~~southern and eastern China (i.e.~~ SC, CC and EC ~~EC),~~ the relative change in rice yield is generally small (<5%) and the model agreement ~~of the model pairs~~ on the change direction is low. These results indicate that climate change may benefit rice yield~~production~~ in the northern and western China while its~~climate change~~ impact ~~on rice yield~~ in the southern and eastern China is inconclusive.

Fig. 6 shows the relative changes in soybean yield at 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 the NEC and NWC with high model agreement on the change direction. In the NEC and XJ, the soybean yield would increase by more than 10% at the end of the 21st century. In the 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 the 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 the NC. These results indicate that climate change would benefit soybean yield in the NEC, NWC and XJ but its impact in the other regions is inconclusive.

4. Fig.7 shows the relative changes in wheat yield at 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 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 the 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 the SC and a high yield in the SWC for wheat, which suggests that ~~Discussions~~ ~~Numerous studies have examined the effects of future~~ climate change would threaten wheat production in the SC and benefit wheat production in the 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 of ~~on~~ crop production

Fig. 8 shows the MMs of the relative~~yields of China. The projected~~ 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 is at the main planting areas in the 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 the 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 the regions outside the traditional agricultural areas but decrease in the main agricultural areas in the eastern China. The relative change in wheat yield (Fig. 8d) is negative across China except for a small area in the

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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 at the prefectures of China at the end of the 21st century. The maize yield would decrease in most prefectures of the SWC, NC and NEC, and would increase in most prefectures of the NWC, NEC and SC (Fig. S1a). The yields of rice and soybean would increase in the most prefectures in China (Fig. S1b,c). The relative change in wheat yield (Fig. S1d) is negative in China except for some prefectures in the 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 the 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 taking 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 extends across most agricultural areas in China including the NC, SC, XJ, and some parts of the NEC and NWC, suggesting that a high climate risk for maize production (Fig. 9). The high risk areas for wheat yield include the 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 the NEC to SWC which is outside the traditional agricultural area. The prefectures with high resilience of crop yield are mainly located in the western and Northeast China (Fig. S3). The prefectures with high risk of crop yield are located in the 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 21st century. The STDs from the crop model ensembles are more than 60% in the Tibet Plateau, suggesting the 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 the eastern China. The model spread for soybean and wheat is more than 50% in many parts of the eastern China, suggesting the model uncertainty is especially large for these crop types. The model spread (i.e. STD of in the relative change of yield) arising from the GGCropMs is larger than that arising from the GCMs in most part of China. The uncertainty arising from the GCMs is generally small (less than 20%) in the eastern China, while is the uncertainty is more than 30% for soybean and wheat over a large area in the 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~~from various~~ crop models is still high (i.e.~~under different climate change experiments often show large differences (e.g.~~ Guo et al., 2010; Tao & Zhang, 2011; Wang et al., 2011; Ye et al., 2013). ~~It seems the state-of-art of GGCMs cannot simulate well the crop yield in the historical period and there is a large model spread in the projected future crop yield change.~~ Moreover, change in ~~future~~ water availability (Tang & Lettenmaier, 2012; Schewe et al., 2014;~~2013;~~ Piontek et al., 2014), which~~2013), which is not~~

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~~accounted for in this study,~~ might lead to a cropland conversion ~~of cropland~~ from irrigated to rain-fed~~rainfed~~ management ~~and a consequent reduction of crop yield~~ (Elliott et al., 2014), are not ~~2013). Furthermore, no adaptation options are~~ considered in this study. Furthermore, we used the model outputs from ISI-MIP and no further adaptation measures are considered.~~the GGCMs.~~ It is possible that the adaptation measures such as changing sowing date and planting area could~~can~~ partially or even totally offset the negative effects of climate change (Yun et al., 2007; Meza et al., 2009; Olmstead et al., 2011). These suggest that the inherent model uncertainty would be a major issue in assessing climate change impacts on crop yield (Asseng et al., 2013; Rosenzweig et al., 2014).~~2013).~~ Future assessment of climate change impacts on crop yield should apply~~use~~ the further improved models ~~applied~~ in a localized setting in China and consider a wide variety of adaptation options.

The simulated crop yields with the CO_2 effects would generally increase in~~over~~ the high-altitude and cold regions in a warming climate. It suggests that climate warming may ~~in the future would~~ allow agriculture to move northward or upward into regions where are currently less ~~un~~suitable for ~~the~~ crops. The simulated crop yields show mixed patterns of increasing and decreasing changes in the current main agricultural area in ~~the~~ eastern China. ~~The simulated crop yield may decrease in a warming climate if present agronomic management was kept because present agronomic management has adapted to the current climate (Xiong et al., 2007). Maize and wheat seem sensitive to the rise in temperature in the eastern China.~~ Climate change is unlikely to benefit maize and wheat productions in the traditional main agricultural area in ~~the~~ eastern China but might benefit rice production. The 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 would largely decrease while the simulations with the CO_2 effect might increase. The important role of the CO_2 effect is also discussed in the 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 many 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 fertilization 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~~The changes in potential yield of the major crops (maize, rice, wheat, and soybean) in China under future climate change are assessed by using crop models forced by the latest climate change experiments generated for IPCC AR5 and made available by ISI-MIP. The~~ 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 ~~of the model pairs on the change direction~~ is low. The response of potential crop

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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 potential yield of maize would decrease in NC, CC and SC and increase in NWC in the next a few decades. The potential yield of rice shows generally increasing trend with high model agreement in NEC, NC, NWC and XJ. The potential yield of soybean would increase in NEC, SWC, NWC and XJ. The analysis shows a transition to a sustained lower yield in SC and a higher yield in SWC for wheat. The wheat yield decrease in SC and increase in SWC become obvious after the 2030s.~~

The response of crop yield to ~~In summary, the analysis shows~~ climate change shows large differences between regions. Climate change~~might benefit rice production as the potential rice yields may increase in a large portion of China. It is possible climate change~~ would benefit soybean and rice yields in~~wheat productions over~~ the high-altitude and cold regions where are currently unsuitable for agriculture. Expanding rice and soybean planting areas to the NEC and SWC~~the crop productions to those regions, when applicable,~~ 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,~~However, the potential yield of maize, soybean and wheat~~ would largely decrease in a warming world.~~large portion of eastern China, the current main crop planting areas such as NC. The risk for maize production is high in NC, SC, XJ, and parts of NEC and NWC, and the risk for wheat production is high in SC, XJ and a part of EC.~~ Development of new agronomic management strategy ~~for maize and wheat~~ may be useful for coping with climate change in these~~above~~ high risk areas. There are large uncertainties among the model projections. Better understanding of the difference of the crop models, which is the major source of the uncertainty, is essential in interpreting the model results.~~–~~

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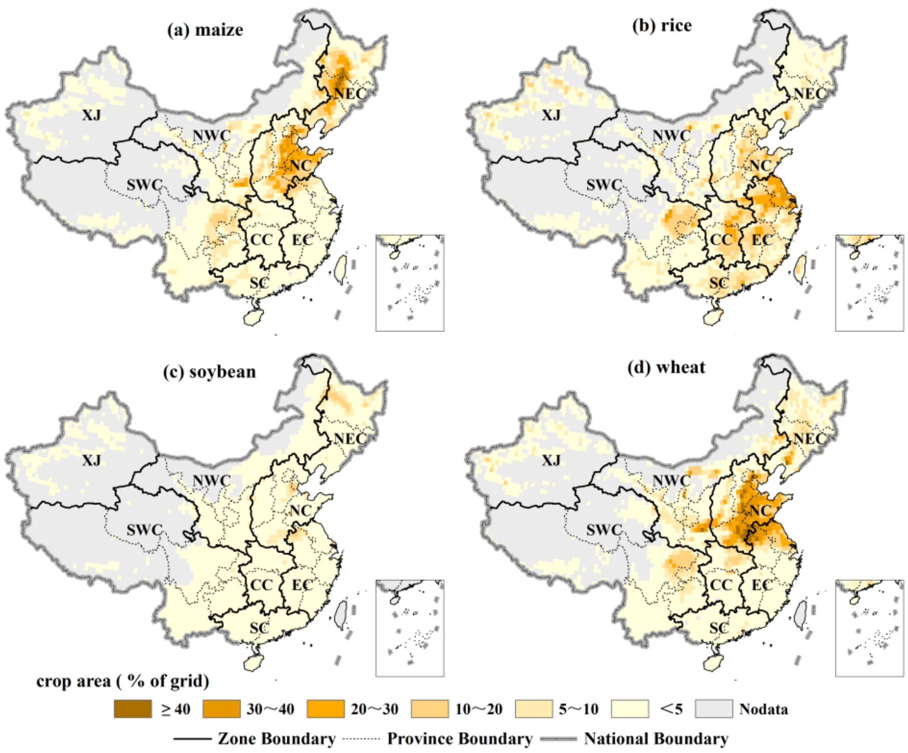

Fig. 1 The 8 regions in China and the crop area (% of grid area) of maize (a), rice (b), soybean (c) and wheat (d). NEC, NC, EC, SC, CC, SWC, NWC and XJ denote Northeast China, North China, Eastern China, South China, Central China, Southwest China, Northwest China and Xinjiang, respectively

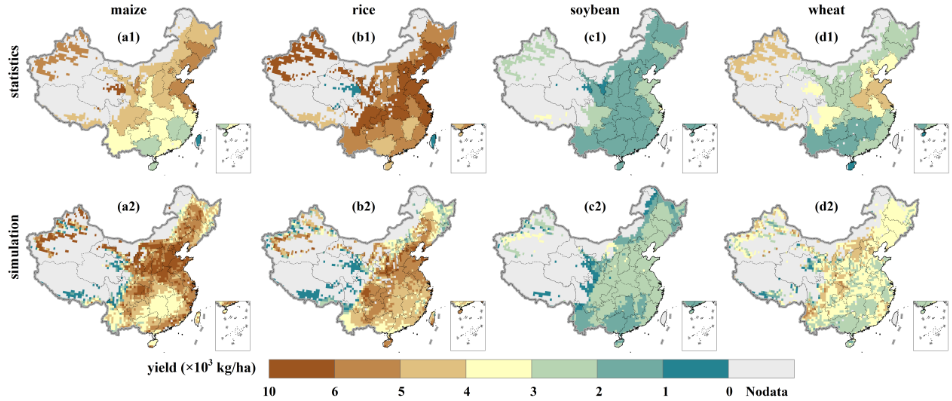

Fig. 2 The MMs of the simulated yields with the CO_2 effect and NBSC reported yields of the 4 major crops in China during 1981-2010. The upper panels are the NBSC yields and lower panels are the simulated yields. The median of the simulated crop yield among the GCM-GGCropM pairs are provided at 0.5-degree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

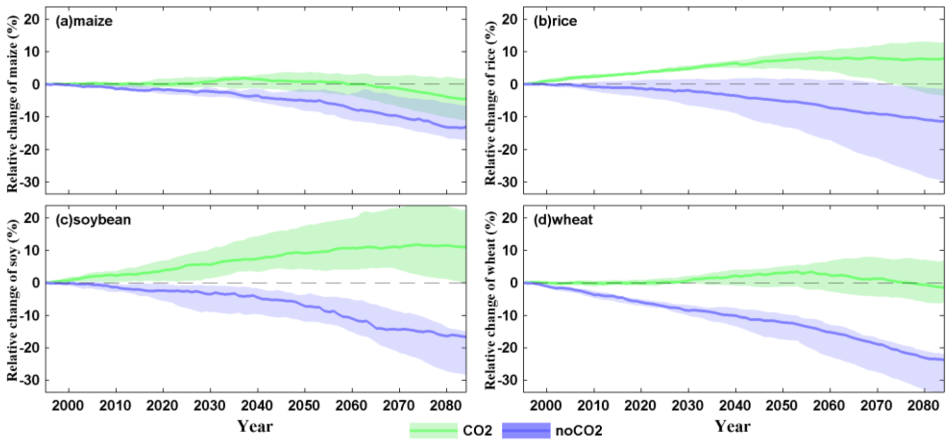

Fig. 3 The relative change of the yield of maize (a), rice (b), soybean (c), and wheat (d) in China under RCP8.5. The blue (green) shade area denotes the inter-quartile range for the simulations with (without) CO_2 effect and the solid line shows the median of the GCM-GGCropM pairs

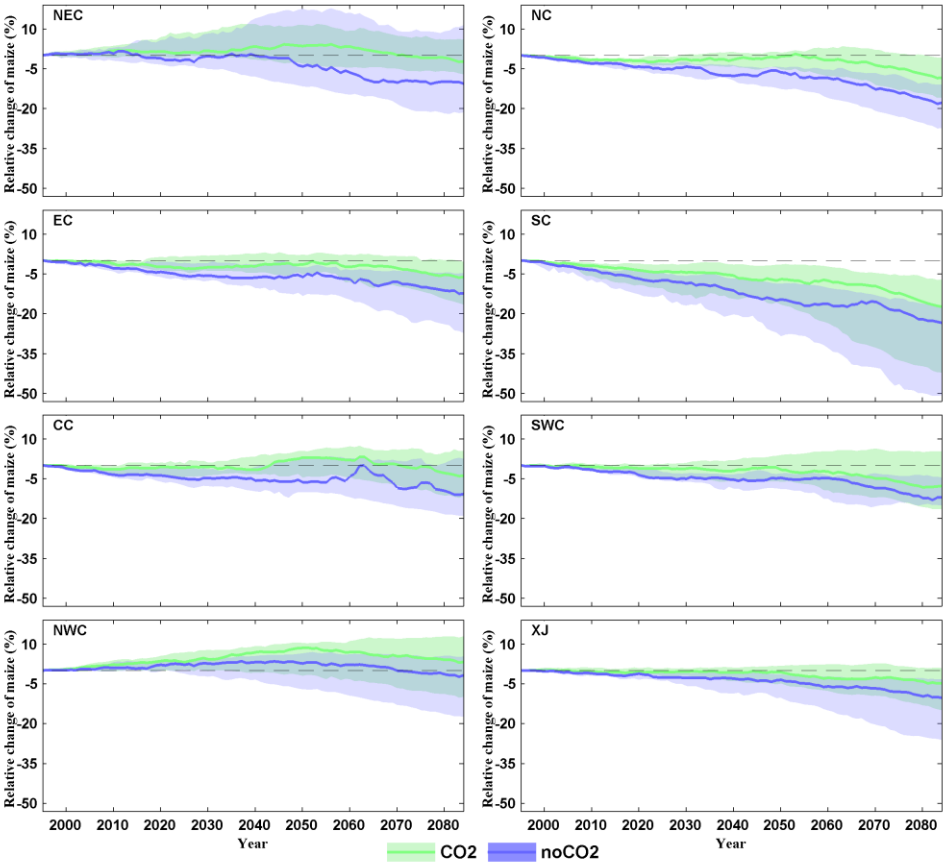

Fig. 4 The relative change of the simulated maize yield at the 8 regions with (without) the CO_2 effect. The MMs and the 25th and 75th percentiles of the model pairs are shown

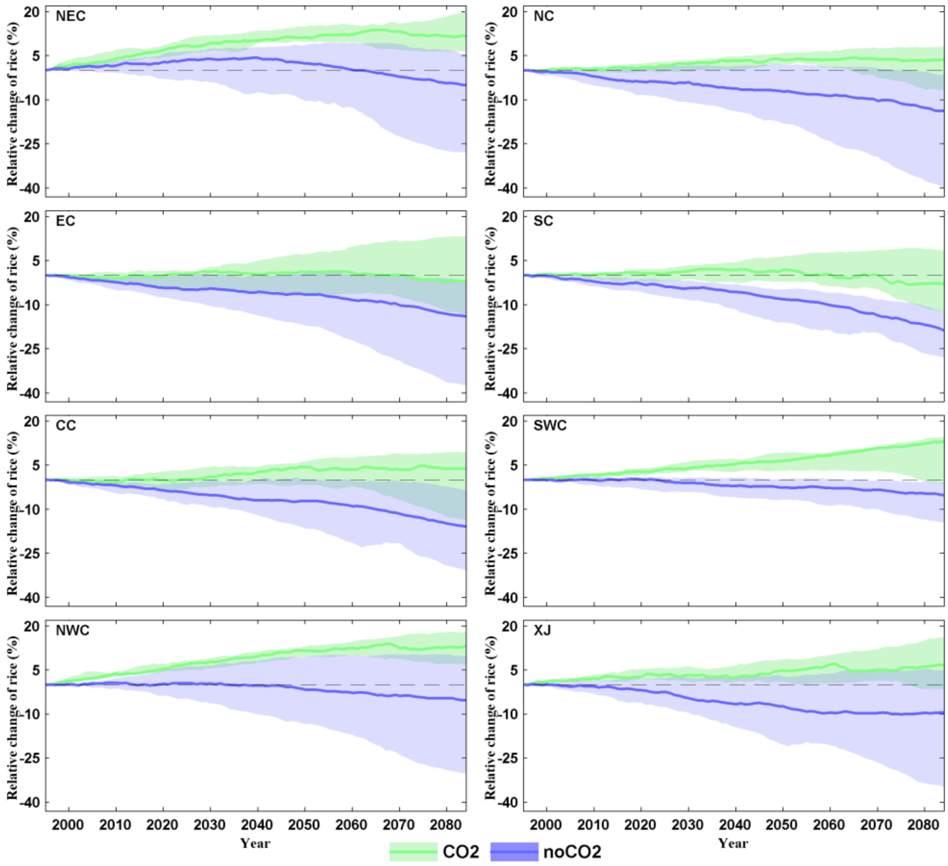

Fig. 5 The relative change of the simulated rice yield at the 8 regions with (without) the CO_2 effect. The MMs and the 25th and 75th percentiles of the model pairs are shown

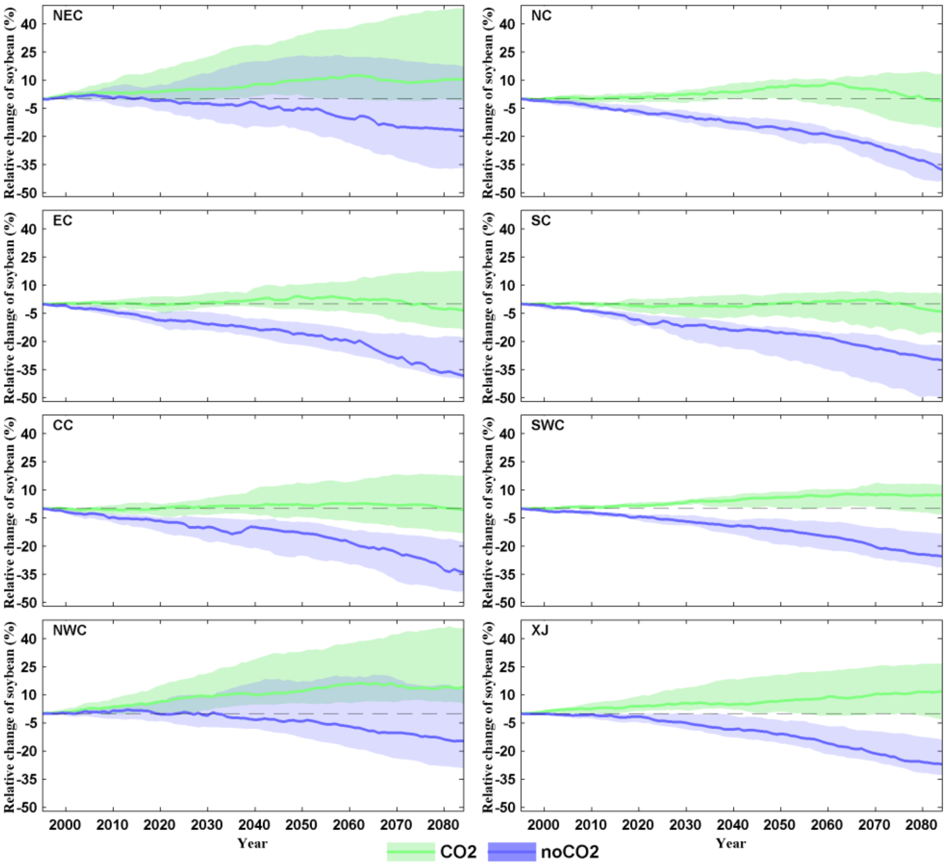

Fig. 6 The relative change of the simulated soybean yield at the 8 regions with (without) the CO_2 effect. The MMs and the 25th and 75th percentiles of the model pairs are shown

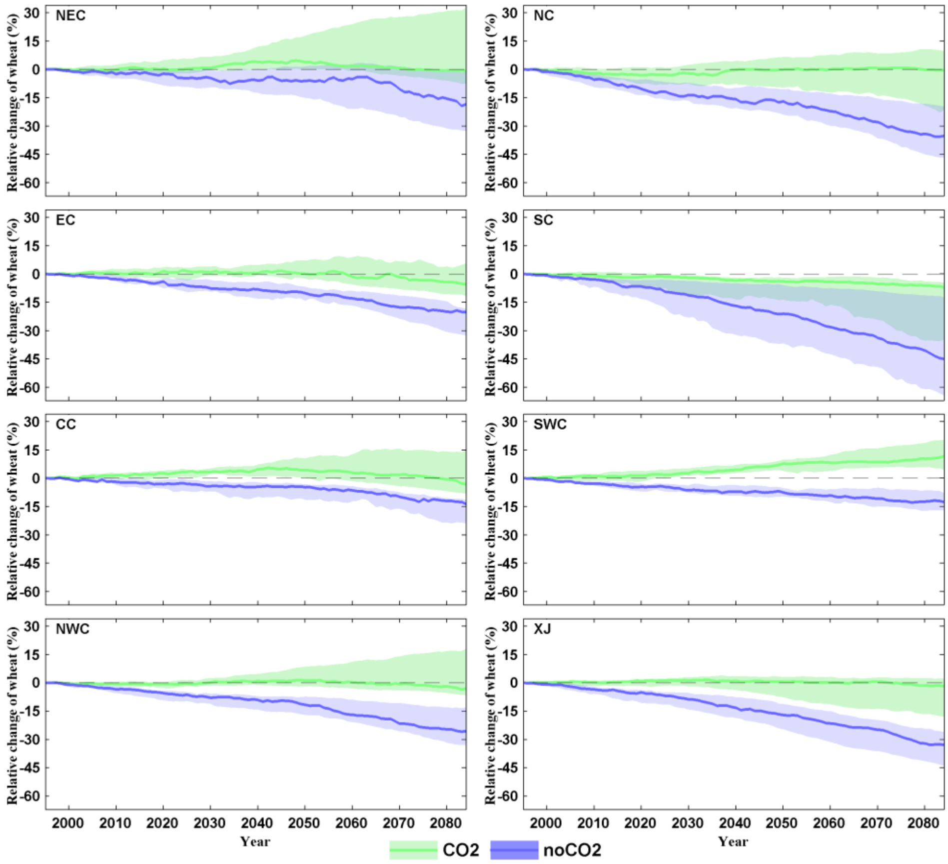

Fig. 7 The relative change of the simulated wheat yield at the 8 regions with (without) the CO_2 effect. The MMs and the 25th and 75th percentiles of the model pairs are shown

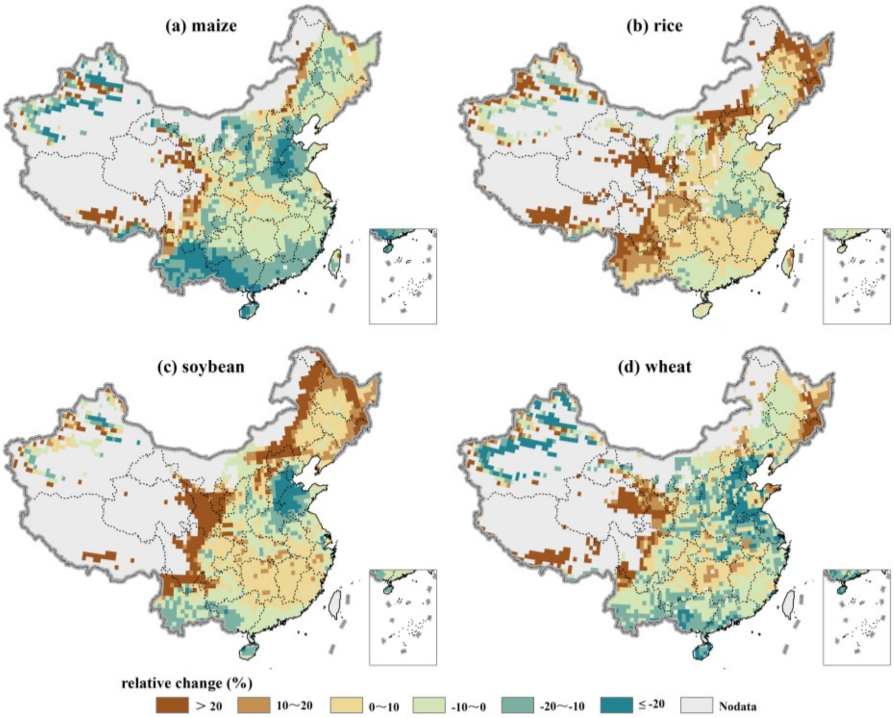

Fig. 8 The MM of the relative change of the simulated yield of maize (a), rice (b), soybean (c), and wheat (d) with the CO_2 effect at the end of the 21st century (2070-2099) comparing with the simulated yield in the historical period (1981-2010)

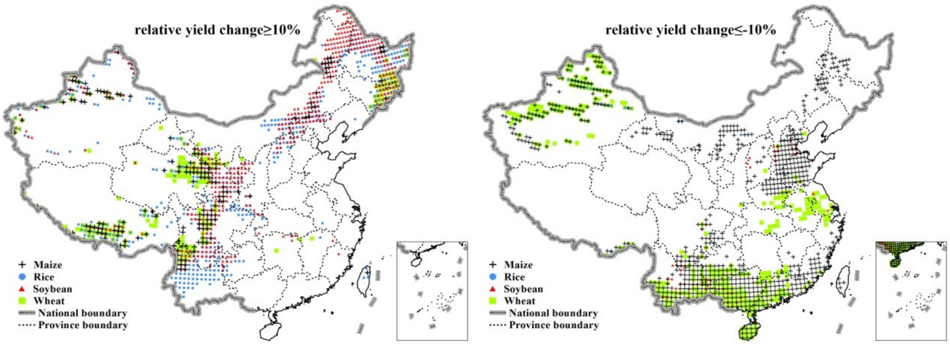

Fig. 9 The high climate resilience areas (left column) and high climate risk areas (right column) for the major crops in China at 0.5 degree grids

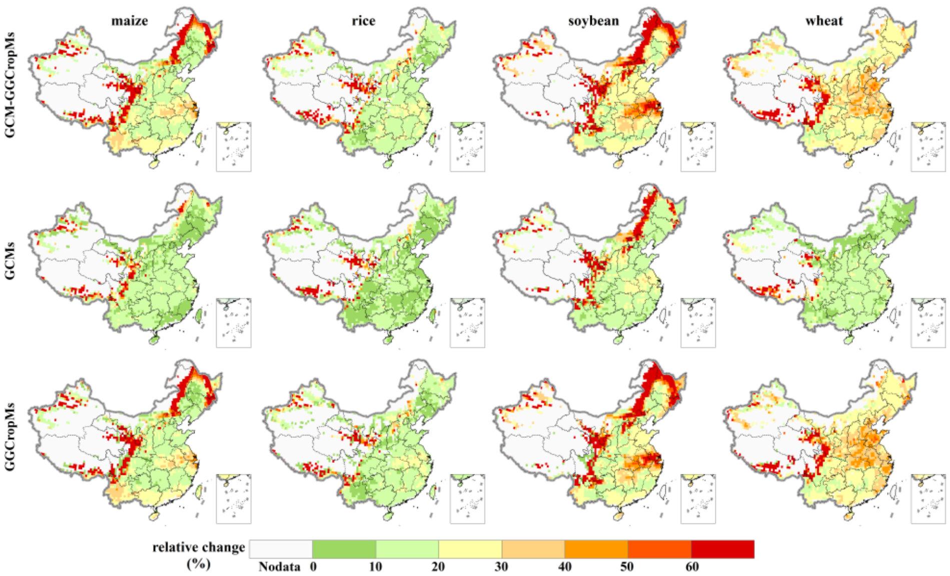

Fig. 10 The model spread of the relative change of the simulated yield of maize, rice, soybean, and wheat with the CO_2 effect at the end of the 21st century (top row) and the model spread induced by GCMs (middle row) and GGCropMs (bottom row)

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).

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