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Impacts of future climate change on potential yields of major crops in China

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Abstract

Climate change may affect crop development and yield, and consequently cast a shadow of doubt over China's food self-sufficiency efforts. In this study we used the model projections of a couple of global gridded crop models (GGCMs) to assess the effects of future climate change on the potential yields of the major crops (i.e. wheat, rice, maize and soybean) over China. The 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 rice may increase over a large portion of China. Climate change may benefit food productions over the high-altitude and cold regions where are outside current main agricultural area. However, the potential yield of maize, soybean and wheat may decrease in a large portion of the current main crop planting areas such as North China Plain. Development of new agronomic management strategy may be useful for coping with climate change in the areas with high risk of yield reduction.

1 Introduction

The linear trend of globally averaged combined land and ocean surface temperature is 0.85 (0.68 to 1.06) °C/100 yr, over the period of 1880–2012 (IPCC, 2013). According to the 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 increased by 0.5–0.8 °C during the past 100 yr (Qin et al., 2005; Ren et al., 2005a, b). The nationwide air temperature would increase by 1.3–2.1 °C in 2020, 2.3–3.3 °C in 2050, and 3.9–6.0 °C in 2100 as compared with air 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 yield and food production have prompted concern worldwide. There are large numbers of studies devoted to assessing the impacts of climate variation over the past few decades (Nicholls, 1997; Lobell et al., 2007; Tao et al., 2008b; 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; Thornton et al., 2009; J. G. Liu et al., 2013). A lot of studies had been carried out to project the change in crop yields in China using crop models (process-based or statistical) with GCM outputs generated for the Fourth Assessment Report of 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). A few studies suggested that the production of major food crops in China might increase under various emission scenarios generated for IPCC AR4 (Z. J. Liu et al., 2013) although projections of climate change impacts on crop yields may be inherently uncertain (Asseng et al., 2013).

Understanding the effects of climate change on crop yields are important for developing adaptation and mitigation measures in agricultural sector to climate change for China. However, most existing assessments were made based on a single crop model forced by climate change experiments generated for IPCC AR4 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. Rice, maize and wheat are the major crops in China. The statistics from National Bureau of Statistics of China (NBSC) (http://data.stats.gov.cn) show that the area of the three major crops 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 reaches 52 million 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. The Inter-Sectoral Impact Model Intercomparison Project (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 Representative Concentration Pathways (RCPs) for IPCC AR5 (Rosenzweig et al., 2014; Elliott et al., 2014). The GGCMs were forced with the bias-corrected climatic variables from RCP 8.5 outputs of 5 global climate models (GCMs). In this study, we used the model projections of a couple of GGCMs in ISI-MIP to assess the effects of future climate change on the yields of the major crops (i.e. wheat, rice, maize and soybean) over China implied by the IPCC AR5 climate change experiments. The model projected yield changes of the crops are illustrated and the uncertainty 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 areas around the year 2000 (Portmann et al., 2010). The MIRCA2000 data consist of all major food crops including wheat, rice, maize and soybean. The data set refers to the period 1998–2002 and has been made available with a spatial resolution of 0.5° by 0.5° by ISI-MIP (Warszawski et al., 2014). The annual crop yield statistics of the four crops in 1981–2010 were provided for each province of China by the National Bureau of Statistics of China (http://www.stats.gov.cn/). The annual harvesting time is 1 in the northern China and 2 or 3 in the southern China. The current GGCMs can't simulate well the multiple harvestings of rice (e.g. Priya et al., 2001; Xiong et al., 2014). We used the yield in a single harvesting time, i.e. early season, mid-season, or single cropping late rice yield of the different rice planting systems (Mei et al., 1988). The yield in the single harvesting time was compared with the simulated potential rice yield of GGCMs.

The simulated potential crop yield data were from the simulations of 4 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 (Deryng et al., 2011). The GGCMs were forced with the bias-corrected climatic data (Hempel et al., 2013) for the historical period (1971–2005 except EPIC of which it is 1980–2010) and the RCP 8.5 future (2006–2099 except EPIC of which it is 2011~2099) climate scenario of 5 GCMs from the Fifth Coupled Model Intercomparison Project (CMIP5) (Taylor et al., 2012). 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. In order to assess the performance of GGCMs, the GGCMs simulations in the historical period were compared with the statistical yields. Table 1 shows an overview of the 5 GCMs and 4 GGCMs. All the 4 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. For more detailed descriptions of the main characteristics of the GGCMs, the readers are referred to Rosenzweig et al. (2014). 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). The average crop yield 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-GGCM pair. There are 5 GCMs and 4 GGCMs, making a total of 20 model pairs for maize, wheat and soybean. Meanwhile, there are 15 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 were computed. The first moving average value was for the period of 1981–2010 (denoted as 1995, the center year of the period) and the other moving average years were also denoted as the center year of the 30-year moving average. The relative crop yield change was computed as the crop yield difference between the moving average year and 1995 (i.e. the historical period of 1981–2010), divided by the crop yield in the historical period. We computed multimodel-ensemble medians (MMs) of the relative crop yield change from all the available GCM-GGCM pairs. We showed the interquartile range of the multimodel ensembles to quantify the uncertainty of the model projections. If MM value of the relative crop yield change at the end of the 21st century (2070–2099) is $> 10\,\%$ ($< -10\,\%$) and more than 75 % model pairs support a positive (negative) change, the model projections suggest that the specific crop has 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.

3 Analysis and results

3.1 Crop area in China

Figure 1 shows the crop area of maize, rice, soybean and wheat in China. The maize planting area is mainly distributed in Northeast China (NEC), North China (NC) and Southwest China (SWC). The rice planting area spreads across the eastern China with large area in East China (EC), Central China (CC), South China (SC), NC, parts of NEC and Sichuan province in SWC. The planting area of soybean is relative small comparing with the areas of maize, rice or wheat. The main planting area of soybean locates in NEC and NC. The wheat planting area is mainly distributed in NC, northern EC, parts of NEC and Sichuan province in SWC.

3.2 Simulated and NBSC statistical yields in 1981–2010

Figure 2 shows the simulated and NBSC statistical yields of China during 1981–2010. The NBSC yields were reported at each province and the crop yield simulations were provided at 0.5° grids. Apparently, the simulated patterns preserve local details inside 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 area such as NEC, NC, and Northwest China (NWC) and are relatively low at CC and SC (Fig. 2a and b). It seems the GGCMs overestimate the maize yields in 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. 2c and d). This is likely due to the limitation of rice model in the GGCMs (Xiong et al., 2014). In the eastern China, both simulation and NBSC data show high rice yield in a belt from the southern NC to Sichuan province in SWC, and low rice yield in the northernmost and southern provinces. In the western China, 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 NBSC yield in most areas of China (Fig. 2e and f). In the main soybean planting areas 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. 2g and h). The NBSC wheat yield is high in the main wheat planting area NC, and part of NWC and XJ, and is low in the southern China. The simulated wheat

yield shows a mixed pattern with higher yield in a belt from NWC to Sichuan province in SWC. Although the model simulation is imperfect in terms of its ability to reproduce the NBSC statistical yield, the 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 statistics illustrates the inherent uncertainty of the state-of-art GGCMs. Due to the large discrepancy between the model simulated yield and NBSC statistics in the historical period, the relative change rather than the absolute difference are analyzed for future changes in crop yields.

3.3 Projected temporal evolution of changes in crop yields

Figure 3 shows the relative change of the simulated yields of maize, rice, soybean, and wheat in China for the period of 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 (e.g. Lin et al., 2005; Ye et al., 2013; Ju et al., 2013). The relative change of maize yield is small (< 5 %). The 25th and 75th percentile envelope of maize yields covers the zero change line throughout the study period, indicating that the model consensus on the change direction does not exist. The simulated maize yield decreases by 3.3 % in the late 21st century although the model uncertainty is high (Fig. 3a). In the ensemble median, there is a transition to a sustained higher yield for rice and soybean that begins in the late 20th century. The simulated rice yield would increase by 8 % in the 2070s and most model pairs support an increasing change. The model agreement on the rice yield increase is very high before the 2040s, suggesting climate change may benefit rice production in the next a few decades. The 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 most model pairs agree on the increase change. The simulated wheat yield shows little change before the 2030s, slightly increase in the 2040s and 2050s, and slight decrease after the 2050s (Fig. 3d). The relative change in wheat yield is generally small (< 5 %) and the agreement of the model pairs on the change direction is low.

Figure 4 shows the relative change in maize yield at the eight regions of China. The median of the simulated maize yields increases slightly before the 2060s and decreases slightly thereafter in the main maize planting area NEC. However, there is no model consensus on the change direction throughout the study period. In another main maize planting area NC, the simulated maize yield decreases slightly with high model agreement before the 2030s, suggesting that maize production in 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 SC, there is a transition to a sustained lower yield for maize. The maize yield would decrease by 18 % 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, SWC and XJ show a generally decreasing change but the model agreements on the change direction are low.

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

4 Discussions

Numerous studies have examined the effects of future climate change on crop yields of China. The projected changes in crop yield from various crop models under different climate change experiments often show large differences (e.g. Guo et al., 2010; Tao and 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 and Lettenmaier, 2012; Schewe et al., 2014; Piontek et al., 2014), which is not accounted for in this study, might lead to a conversion of cropland from irrigated to rainfed management and a consequent reduction of crop yield (Elliott et al., 2014). Furthermore, no adaptation options are considered in the GGCMs. It is possible adaptation measures such as changing sowing date and planting area can partially or 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). Future assessment of climate change impacts on crop yield should use the further improved models applied in a localized setting in China and consider a wide variety of adaptation options.

The simulated crop yields generally increase over the high-altitude and cold regions in a warming climate. It suggests that warming in the future would allow agriculture to move northward or upward into regions currently unsuitable for the crops. The simulated crop yields show mixed patterns of increasing and decreasing change 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.

5 Conclusions

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 agreement of the model pairs on the change direction is low. The response of potential crop yield to climate change shows large regional differences. 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.

In summary, the analysis shows 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 wheat productions over the high-altitude and cold regions where are currently unsuitable for agriculture. Expanding the crop productions to those regions, when applicable, might be a good adaptation option to climate change. However, the potential yield of maize, soybean and wheat would decrease in a 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 the above high risk areas.

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References

Asseng, S., Ewert, F., Rosenzweig, C., Jones, J. W., Hatfield, J. L., Ruane, A. C., Boote, K. J., Thorburn, P. J., Rotter, R. P., Cammarano, D., Brisson, N., Basso, B., Martre, P., Aggarwal, P. K., Angulo, C., Bertuzzi, P., Biernath, C., Challinor, A. J., Doltra, J., Gayler, S., Goldberg, R., Grant, R., Heng, L., Hooker, J., Hunt, L. A., Ingwersen, J., Osborne, T. M., Palosuo, T., Priesack, E., Ripoche, D., Semenov, M. A., Shcherbak, I., Steduto, P., Stockle, C., Stratonovitch, P., Streck, T., Supit, I., Tao, F., Travasso, M., Waha, K., Wallach, D., White, J. W., Williams, J. R., and Wolf, J.: Uncertainty in simulating wheat yields under climate change, Nat. Clim. Change, 3, 827–832, 2013.

Bentsen, M., Bethke, I., Debernard, J. B., Iversen, T., Kirkevåg, A., Seland, Ø., Drange, H., Roelandt, C., Seierstad, I. A., Hoose, C., and Kristjánsson, J. E.: The Norwegian Earth System Model, NorESM1-M – Part 1: Description and basic evaluation of the physical climate, Geosci. Model Dev., 6, 687–720, doi:10.5194/gmd-6-687-2013, 2013.

Cammarano, D., Payero, J., Basso, B., Stefanova, L., and Grace, P.: Adapting wheat sowing dates to projected climate change in the Australian subtropics: analysis of crop water use and yield, Crop Past. Sci., 63, 974–986, 2012

Challiore, A. J., Simelton, E. S., Fraser, E. D., Hemming, D., and Collins, M.: Increased crop failure due to climate change: assessing adaptation options using models and socio-economic data for wheat in China, Environ. Res. Lett., 5, 1–8, 2010.

Deryng, D., Sacks, W. J., Barford, C. C., and Ramankutty, N.: Simulating the effects of climate and agricultural management practices on global crop yield, Global Biogeochem. Cy., 25, GB2006, doi:10.1029/2009GB003765, 2011.

Dunne, J. P., John, J. G., Adcroft, A. J., Griffies, S. M., Hallberg, R. W., Shevliakova, E., Stouffer, R. J., Cooke, W., Dunne, K. A., Harrison, M. J., Krasting, J. P., Malyshev, S. L., Milly, P. C., Phillipps, P. J., Sentman, L. T., Samuels, B. L., Spelman, M. J., Winton, M., Wittenberg, A. T., and Zadeh, N.: GFDL's ESM2 Global Coupled Climate–Carbon Earth System Models, Part I: Physical Formulation and Baseline Simulation Characteristics, J. Climate, 25, 6646–6665, 2012.

Dunne, J. P., John, J. G., Shevliakova, E., Stouffer, R. J., Krasting, J. P., Malyshev, S. L., Milly, P. C., Sentman, L. T., Adcroft, A. J., Cooke, W., Dunne, K. A., Griffies, S. M., Hallberg, W. Q., Harrison, M. J., Levy, H., Wittenberg, A. T., Phillips, P. J., and Zadeh, N.: GFDL's ESM2 Global Coupled Climate–Carbon Earth System Models, Part II: Carbon System Formulation and Baseline Simulation Characteristics, J. Climate, 26, 2247–2267, 2013.

Elliott, J., Deryng, D., Müller, C., Frieler, K., Konzmann, M., Gerten, D., Glotter, M., Florke, M., Wada, Y., Best, N., Eisner, S., Fekete, B. M., Folberth, C., Foster, I., Gosling, S. N., Haddeland, I., Khabarow, N., Ludwig, F., Masaki, Y., Olin, S., Rosenzweig, C., Ruane, A. C., Satoh, Y., Schmid, E., Stacke, T., Tang, Q. H., and Wisser, D.: Constraints and potentials of future irrigation water availability on agricultural production under climate change, P. Natl. Acad. Sci. USA, 111, 3239–3244, doi:10.1073/pnas.1222474110, 2014.

Elliott, J., Glotter, M., Best, N., Wilde, M., Glotter, M., and Foster, I.: The Parallel System for Integrating Impact Models and Sectors (pSIMS), Proceedings of the 2013 XSEDE Conference, 2013.

Elliott, J., Glotter, M., Best, N., Wilde, M., Glotter, M., and Foster, I.: Future scenarios of European agricultural land use I. estimating changes in crop productivity, Agr. Ecosyst. Environ., 107, 101–106, 2005.

Gao, Y. G., Wang, Y. G., Nan, R., Yan, P., and Yang, X. Q.: Identification and application of thermal indexes of main cultivated soybean varieties in Heilongjiang Province, Chinese J. Agrometeorol., 26, 200–204, 2005.

Hempel, S., Frieler, K., Warszawski, L., Schewe, J., and Piontek, F.: A trend-preserving bias correction – the ISI-MIP approach, Earth Syst. Dynam., 4, 219–236, doi:10.5194/esd-4-219-2013, 2013.

IPCC – Intergovernmental Panel on Climate Change: Summary for Policymakers, in: Climate Change 2013: The Physical Science Basis, in: Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change, edited by: Stocker, T. F., Qin, D., Plattner, G.-K., Tignor, M., Allen, S. K., Boschung, J., Nauels, A., Xia, Y., Bex, V., and Midgley, P. M., Cambridge University Press, Cambridge, UK and New York, NY, USA., 2013.

Iversen, T., Bentsen, M., Bethke, I., Debernard, J. B., Kirkevåg, A., Seland, Ø., Drange, H., Kristjansson, J. E., Medhaug, I., Sand, M., and Seierstad, I. A.: The Norwegian Earth System Model, NorESM1-M – Part 2: Climate response and scenario projections, Geosci. Model Dev., 6, 389–415, doi:10.5194/gmd-6-389-2013, 2013.

Izauurade, R. C., Williams, J. R., McGill, W. B., Rosenberg, N. J., and Quiroga Jakas, M. C.: Simulating soil C dynamics with EPIC: Model description and testing against long-term data, Ecol. Model., 192, 362–384, 2006.

Jones, C. D., Hughes, J. K., Bellouin, N., Hardiman, S. C., Jones, G. S., Knight, J., Liddicoat, S., O'Connor, F. M., Andres, R. J., Bell, C., Boo, K.-O., Bozzo, A., Butchart, N., Cadule, P., Corbin, K. D., Doutriaux-Boucher, M., Friedlingstein, P., Gornall, J., Gray, L., Halloran, P. R., Hurtt, G., Ingram, W. J., Lamarque, J.-F., Law, R. M., Meinshausen, M., Osprey, S., Palin, E. J., Parsons Chini, L., Raddatz, T., Sanderson, M. G., Sellar, A. A., Schurer, A., Valdes, P., Wood, N., Woodward, S., Yoshioka, M., and Zerroukat, M.: The HadGEM2-ES implementation of CMIP5 centennial simulations, Geosci. Model Dev., 4, 543–570, doi:10.5194/gmd-4-543-2011, 2011.

Jones, J. W., Hoogenboom, G., Poter, C. H., Boote, K. J., Batchelor, W. D., Hunt, L. A., Wilkens, P. W., Singh, W., Gijsman, A. J., and Ritchie, J. T.: The DSSAT cropping system model, Eur. J. Agron., 18, 235–265, 2003.

Jones, P. G. and Thornton, P. K.: The potential impacts of climate change on maize production in Africa and Latin America in 2055, Global Environ. Change, 13, 51–59, 2003.

Joshi, N. P., Maharjan, K. L., and Luni, P.: Effect of climate variables on yield of major food-crops in Nepal – a time-series analysis, Graduate school for international development and cooperation, Hiroshima University, Hiroshima, 2011.

Ju, H., Lin, E. D., Wheeler, T., Andrew, C., and Jiang, S.: Climate change modeling and its roles to Chinese crops yield, J. Integrat. Agr., 12, 892–902, 2013.

Li, K. N., Yang, X. G., Mu, C. Y., Xu, H. J., and Chen, F.: The possible effects of global warming on cropping systems in China VIII – the effects of climate change on planting boundaries of different winte-spring varieties of winter wheat in China, Scient. Agr. Sin., 46, 1583–1594, 2013.

Lin, E. D., Xiong, W., Ju, H., Xu, Y. L., Li, Y., Bai, L. P., and Xie, L. Y.: Climate change impacts on crop yield and quality with CO_2 fertilization in China, Philos. T. Roy. Soc., 360, 2149–2154, 2005.

Lindeskog, M., Arneth, A., Bondeau, A., Waha, K., Seaquist, J., Olin, S., and Smith, B.: Implications of accounting for land use in simulations of ecosystem carbon cycling in Africa, Earth Syst. Dynam., 4, 385–407, doi:10.5194/esd-4-385-2013, 2013.

Liu, J. G.: A GIS-based tool for modeling large-scale crop-water relations, Environ. Model. Softw., 24, 411–422, 2009.

Liu, J. G., Williams, J., Zehnder, A. J., and Yang, H.: GEPIC – modelling wheat yield and crop water productivity with high resolution on a global scale, Agricult. Syst., 94, 478–493, 2007.

Liu, J. G., Zehnder, A. J., and Yang, H.: Global consumptive water use for crop production: the importance of green water, Water Resour. Res., 45, W05428, doi:10.1029/2007WR006051, 2009.

Liu, J. G., Folberth, C., Yang, H., Rockstrom, J., Abbaspour, K., and Zehnder, A. J.: A global and spatially explicit assessment of climate change impacts on crop production and consumptive water use, PLOS, 8, 1–13, 2013.

Liu, Z. J., Hubbard, K. G., Lin, X. M., and Yang, X. G.: Negative effects of climate warming on maize yield are reversed by the changing of sowing date and cultivar selection in Northeast China, Global Change Biol., 19, 3481–3492, 2013.

Lobel, D. B. and Field, C. B.: Global scale climate-crop yield relationships and the impacts of recent warming, Environ. Res. Lett., 2, 1–8, 2007.

Lv, Z. F., Liu, X. J., Cao, W. X., and Zhu, Y.: Climate change impacts on regional winter wheat production in main wheat production regions of China, Agr. Forest Meteorol., 171, 234–248, 2013.

Mei, F. Q., Wu, X. Z., Yao, C. X., Li, L. P., Wang, L., and Chen, Q. Y.: Rice cropping regionalization in China, Chinese J. Rice Sci., 2, 97–110, 1988.

Meza, F. J. and Silva, D.: Dynamic adaptation of maize and wheat production to climate change, Climatic Change, 94, 143–156, 2009.

Mignot, J. and Bony, S.: Presentation and analysis of the IPSL and CNRM climate models used in CMIP5, Clim. Dynam., 40, 2089, doi:10.1007/s00382-013-1720-1, 2013.

Nicholls, N.: Increased Australian wheat yield due to recent climate trends, Nature, 387, 484–485, 1997.

Olmstead, A. L. and Rhode, P. W.: Adapting North American wheat production to climatic challenges, 1839–2009, P. Natl. Acad. Sci. USA, 108, 480–485, 2011.

Ortiz, R., Sayre, K. D., Govaerts, B., Gupta, R., Subbarao, G. V., Ban, T., Hodson, D., Dixon, J. M., Ortiz-Monasterio, J. I., and Reynolds, M.: Climate change: Can wheat beat the heat?, Agr. Ecosyst. Environ., 126, 46–58, 2008.

Parry, M. L., Rosenzweig, C., Igleias, A., Livermore, M., and Fischer, G.: Effect of climate change on global food production under SRES emissions and socio-economic scenarios, Global Environ. Change, 14, 53–67, 2004.

Piontek, F., Müller, C., Pugh, T. A., Clark, D. B., Deryng, D., Elliott, J., Gonzalez, F. J., Florke, M., Folberth, C., Franssen, W., Frieler, K., Friend, A. D., Gosling, S. N., Hemming, D., Khabarov, N., Kin, H., Lomas, M. R., Masaki, Y., Mengel, M., Morse, A., Neumann, K., Nishina, K., Ostberg, S., Pavlick, R., Ruane, A. C., Schewe, J., Schmid, E., Stacke, T., Tang, Q. H., Tessler, Z. D., Tompkins, A. M., Warszawski, L., Wisser, D., and Schellnhuber, H. J.: Multisectoral climate impact hotspots in a warming world, P. Natl. Acad. Sci. USA, 111, 3233–3238, doi:10.1073/pnas.1222471110, 2014.

Portmann, F. T., Siebert, S., and Döll, P.: MIRCA2000 – Global monthly irrigated and rainfed crop areas around the year 2000: A new high-resolution data set for agricultural and hydrological modeling, Global Biogeochem. Cy., 24, 1–24, 2010.

Priya, S. and Shibasaki, R.: National spatial crop yield simulation using GIS-based crop production mode, Ecol. Mlodel., 135, 113–129, 2001.

Qin, D. H.: Climate change sciences into the 21st century: facts, impact and strategies addressing climate change, Sci. Technol. Rev., 7, 4–7, 2004.

Qin, D. H.: Climate and environmental evolution in China (I), Resour. Environ. Develop., 3, 1–2, 2004.

Qin, D. H., Ding, Y. H., Su, J. L., Ren, J. W., Wang, S. W., Wu, R. S., Yang, X. Q., Wang, S. M., Liu, S. Y., Dong, G. R., Lu, Q., Huang, Z. G., Du, B. L., and Luo, Y.: Assessment of climate and environment changes in China (I): climate and environment changes in China and their projection, Adv. Clim. Change Res., 1, 4–9, 2005.

Ren, G. Y., Guo, J., Xu, M. Z., Chu, Z. Y., Zhang, L., Zou, X. K., Li, Q. X., and Liu, X. N.: Climate changes of China's mainland over the past half century, Acta Meteorol. Sin., 63, 942–956, 2005a.

Ren, G. Y., Chu, Z. Y., Zhou, Y. Q., Xu, M. Z., Wang, Y., Tang, G. L., Zhai, P. M., Shao, X. M., Zhang, A. Y., Chen, Z. H., Guo, J., Liu, H. B., Zhou, J. X., Zhao, Z. C., Zhang, L., Bai, H. Z., Liu, X. F., and Tang, H. Y.: Recent progresses in studies of regional temperature changes in China, Clim. Environ. Res., 10, 701–716, 2005b.

Rodomiro, O., Kenneth, D. S., Bram, G., Gupta, R., Subbarao, G. V., Ban, T., Hodson, D., Dixon, J. M., Ortiz-Monasterion, J. I., and Reynolds, M.: Climate change: can wheat beat the heat?, Agr. Ecosyst. Environ., 126, 46–58, 2008.

Rosenzweig, C., Elliot, J., Deryng, D., Ruane, A. C., Muller, C., Arneth, A., Boote, K. J., Folberth, C., Glotter, M., Khabarov, A. C., Neumann, K., Piontek, F., Pugh, T. A., Schmid, E., Stehfest, E., Yang, H., and Jones, J. M.: Assessing agricultural risks of climate change in the 21st century in a global gridded crop model intercomparison, P. Natl. Acad. Sci., 111, 3268–3273, doi:10.1073/pnas.1222463110, 2014.

Schewe, J., Heinke, J., Gerten, D., Haddeland, I., Arnell, N. W., Clark, D. B., Dankers, R., Eisner, S., Fekete, B. M., Colon-Gonzalez, F. J., Gosling, S. N., Kim, H., Liu, X. C., Masaki, Y., Portmann, F. T., Satoh, Y., Stacke, T., Tang, Q. H., Wada, Y., Wisser, D., Albrecht, T., Frieler, K., Piontek, F., W arszawski, L., and Kabat, P.: Multimodel assessment of water scarcity under climate change, P. Natl. Acad. Sci. USA, 111, 3245–3250, doi:10.1073/pnas.1222460110, 2014.

Tang, Q. H. and Lettenmaier, D. P.: 21st century runoff sensitivities of major global river basins, Geophys. Res. Lett., 39, L06403, doi:10.1029/2011GL050834, 2012.

Tao, F. L. and Zhang, Z. : Climate change, wheat productivity and water use in the North China Plain: A new super-ensemble-based probabilistic projection, Agr. Forest Meteorol., 170, 146–165, 2013.

Tao, F. L., Hayashi, Y., Zhang, Z., Sakamoto, T., and Yolozawa, M.: Global warming, rice production, and water use in China: developing a probabilistic assessment, Agr. Forest Meteorol., 148, 94–110, 2008a.

Tao, F. L., Yolozawa, M., Liu, J. Y., and Zhang, Z.: Climate-crop yield relationships at provincial scales in China and the impacts of recent climate trends, Clim. Res., 38, 83–94, 2008b.

Taylor, K., Stouffer, R., and Meehl, G.: An overview of CMIP5 and the experiment design, B. Am. Meteorol. Soc., 93, 485–498, 2012.

Tornton, P. K., Jones, P. G., Alagarswamy, G., and Andresen, J.: Spatial variation of crop yield response to climate change in East Africa, Global Environ. Change, 19, 54–65, 2009.

Tingem, M., Rivington, M., Bellocchi, G., Azam-Ali, S., and Colls, J.: Comparative assessment of crop cultivar and sowing dates as adaptation choice for crop production in response to climate change in Cameroon, Afr. J. Plant Sci. Biotechnol., 2, 10–17, 2008.

Wahaa, K., Muller, C., Bondeau, A., Dietrich, J. P., Kurukulasuriya, P., Heinke, J., and Lotze-Campen, H.: Adaptation to climate change through the choice of cropping system and sowing date in sub-Saharan Africa. Global Environ. Change, 23, 130–143, 2013.

Wang, M., Li, Y. P., Ye, W., Bornman, J. F., and Yan, X. D.: Effects of climate change on maize production and potential adaptation measures: a case study in Jilin Province, China, Clim. Res., 46, 223–242, 2011.

Wang, Y. Q. and Ma, S. M.: Technological options of regional agricultural adaptation to climate change in China, Chinese J. Agrometeorol., 30, 51–56, 2009.

Warszawski, L., Frieler, K., Pontek, F., Piontek, F., Serdeczny, O., and Schewe, J.: Research Design of the Intersectoral Impact Model Intercomparison Project (ISI-MIP), P. Natl. Acad. Sci., 111, 3228–3232, doi:10.1073/pnas.1312330110, 2014.

Watanabe, S., Hajima, T., Sudo, K., Nagashima, T., Takemura, T., Okajima, H., Nozawa, T., Kawase, H., Abe, M., Yokohata, T., Ise, T., Sato, H., Kato, E., Takata, K., Emori, S., and Kawamiya, M.: MIROC-ESM 2010: model description and basic results of CMIP5-20c3m experiments, Geosci. Model Dev., 4, 845–872, doi:10.5194/gmd-4-845-2011, 2011.

Williams, J. R.: The EPIC Model, in: Computer Models of Watershed Hydrology, edited by: Singh, V. P., Water Resources Publications, Highlands Ranch, Colorado, 1995.

Williams, J. R., Jones, C. A., and Dyke, P. T.: EPIC-Erosion/Productivity Impact Calculator, United States Department of Agriculture Publications, Littleton, CO, 909–1000, 1990.

Xiong, W., Matthews, R., Holman, I., Lin, E. D., and Xu, Y. L.: Modelling China's potential maize production at regional scale under climate change, Climate Change, 85, 433–451, 2007.

Xiong, W., Balkovic, J., Velde, M. et al.: A calibration procedure to improve global rice yield simulations with EPIC, Ecol. Mlodel., 273, 128–139, 2014.

Yang, X. G., Liu, Z. J., and Chen, F.: The possible effects of global warming on cropping systems in China VI. possible effects of future climate change on northern limits of cropping system in China, Scient. Agricult. Sin., 44, 1562–1570, 2012.

Ye, L. M., Tang, H. J., Wu, W. B., Yand, P., Nelson, G. C., Croz, D. M., and Palazzo, A.: Chinese food security and climate change: agriculture futures, Economics Discussion Papers No. 2013-2, Kiel Institute for the World Economy, Kiel, 2013.

Yun, Y. R., Fang, X. Q., Wang, Y., Tao, J. D., and Qiao, D. F.: Main grain crops structural change and its climate background in Heilongjiang Province during the past two decades, J. Nat. Resour., 20, 697–695, 2005.

Yun, Y. R., Fang, X. Q., Wang, L. Y., and Tian, Q.: The changes of crop planting boundaries response to climate warming in China, Crops, 3, 20–23, 2007.

Zhou, Q. F, Dai, E. F., Wu, S. H., Pan, T., and Chen, X. W.: Risk assessment on food crops supply-demand balance under climate change in China, Acta Scientiarum Naturalium Universitatis Pekinensis, 47, 1105–1115, 2011.

Table 1. The relative change of the simulated yields of maize, rice, soybean, and wheat in China. The relative change was relative to that model's climatology in 1981–2010 (denoted as 1995). The 30-year moving average results are shown to emphasize low-frequency variability that is of interest for food production and security. The median (black line) of the relative change distribution among the GCM-GGCM pairs are shown, and the 25–75 % range of all models for each crop is represented in gray.

	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, 2013)
	NorESM1-M	Norwegian Climate Centre	Bentsen et al. (2013); Iversen et al. (2013)
GGCMs	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. (2014); Jones et al. (2003)
	PEGASUS	Tyndall Centre, University of East Anglia UK/McGill University, Canada	Deryng et al. (2011)

Table 2. Simulated and NBSC 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.

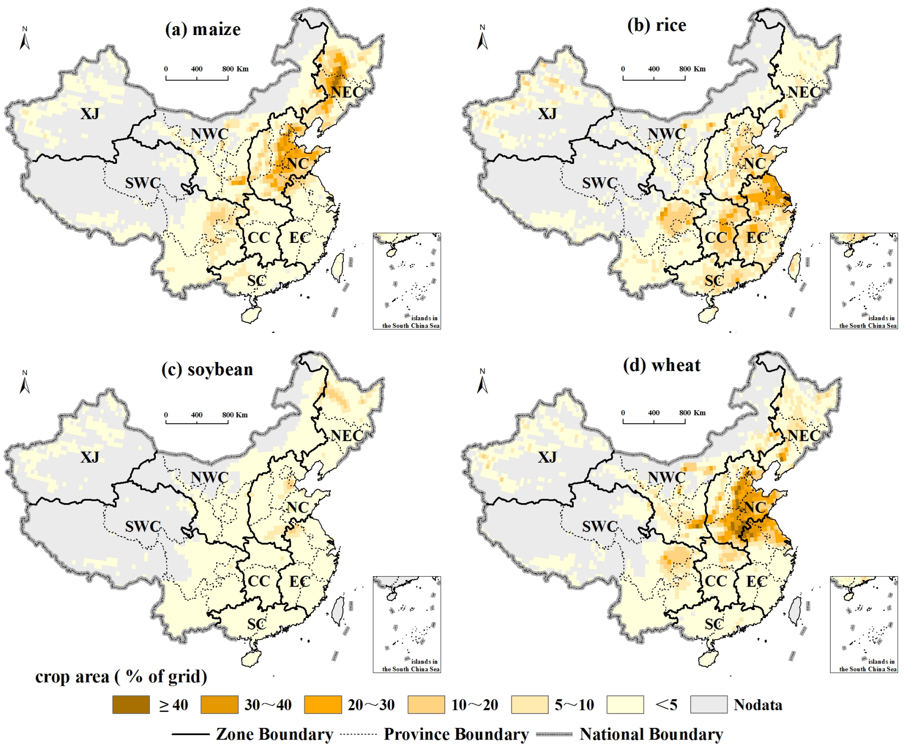

Figure 1. The 8 regions in China and the crop area (% of grid area) of maize, rice, soybean and wheat. NEC, NC, EC, SC, CC, SWC, NWC and XJ denote Northeast China, North China, Eastern China, South China, Central China, Southwest China, Northwest China and Xinjiang, respectively.

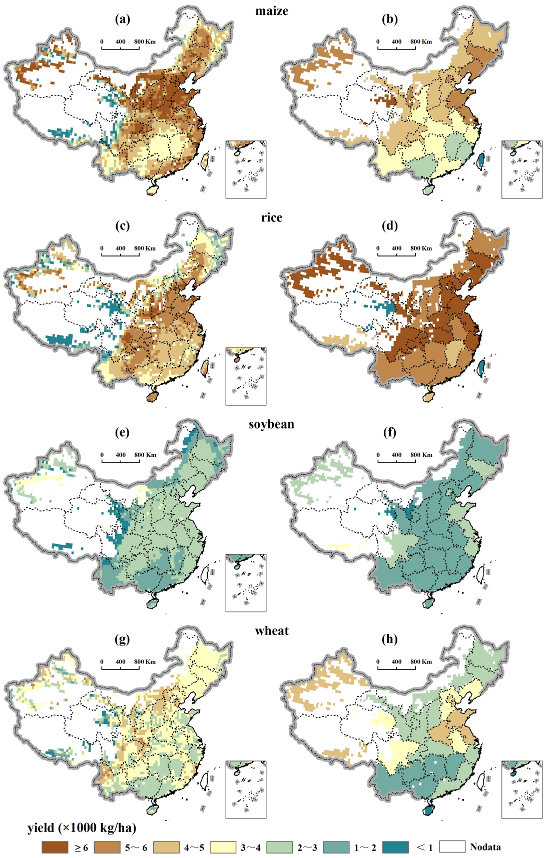

Figure 2. The simulated and NBSC statistical yields of the 4 major crops in China during 1981–2010. The simulated **(a)** and NBSC **(b)** maize yields, simulated **(c)** and NBSC **(d)** rice yields, simulated **(e)** and NBSC **(f)** soybean yields, and simulated **(g)** and NBSC **(h)** yields are shown. The median of the simulated crop yield among the GCM-GGCM pairs are provided at 0.5° grids. The NBSC yield at each province was plotted to the crop area mask shown in Fig. 1.

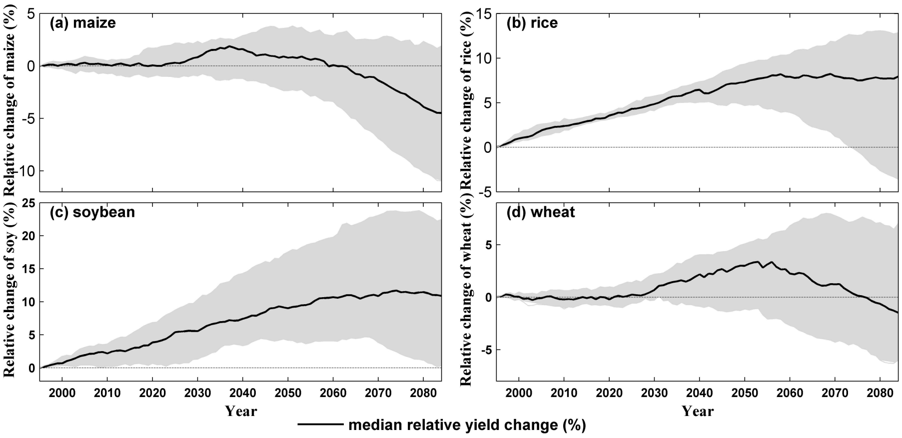

Figure 3. The relative change of the simulated yields of maize, rice, soybean, and wheat in China. The relative change was relative to that model's climatology in 1981–2010 (denoted as 1995). The 30-year moving average results are shown to emphasize low-frequency variability that is of interest for food production and security. The median (black line) of the relative change distribution among the GCM-GGCM pairs are shown, and the 25–75 % range of all models for each crop is represented in gray.

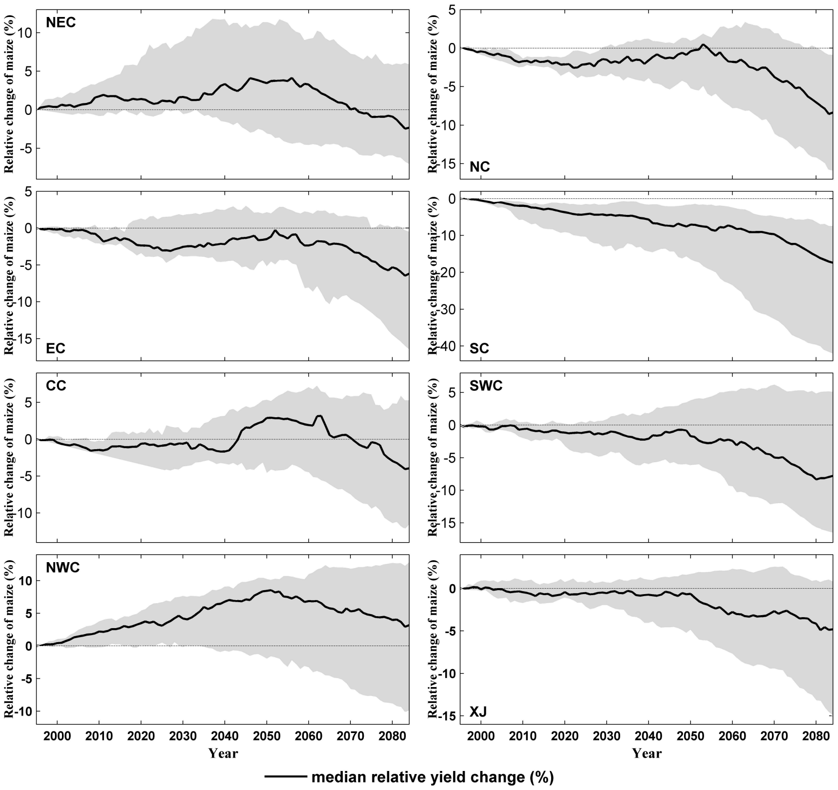

Figure 4. The relative change of the simulated maize yields at the regions of China. The MMs and the 25th and 75th percentiles of the model pairs are shown.

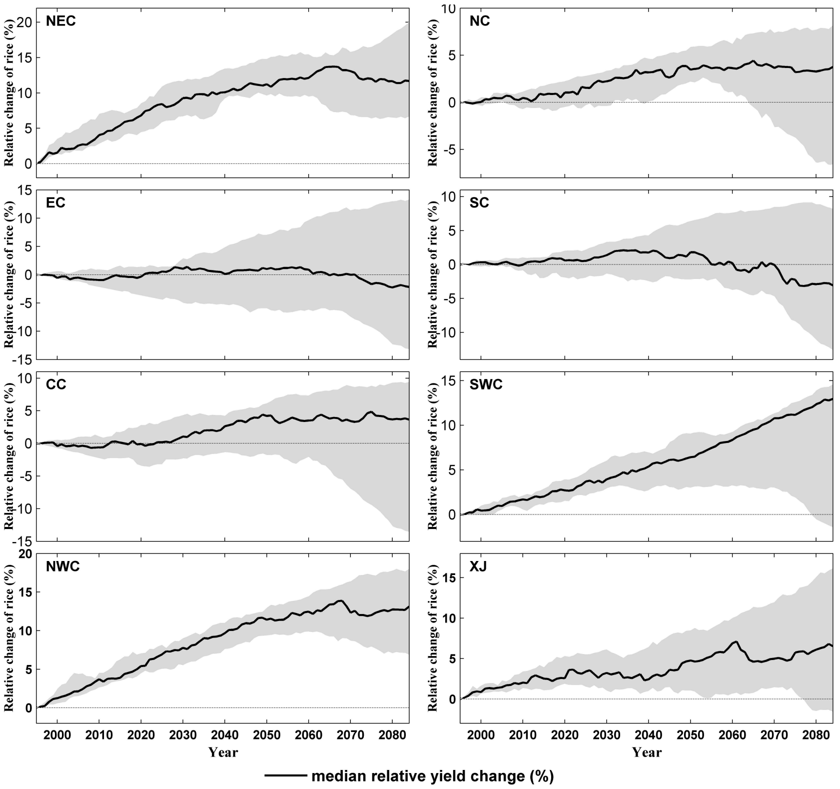

Figure 5. The relative change of the simulated rice yield at the regions of China. The MMs and the 25th and 75th percentiles of the model pairs are shown.

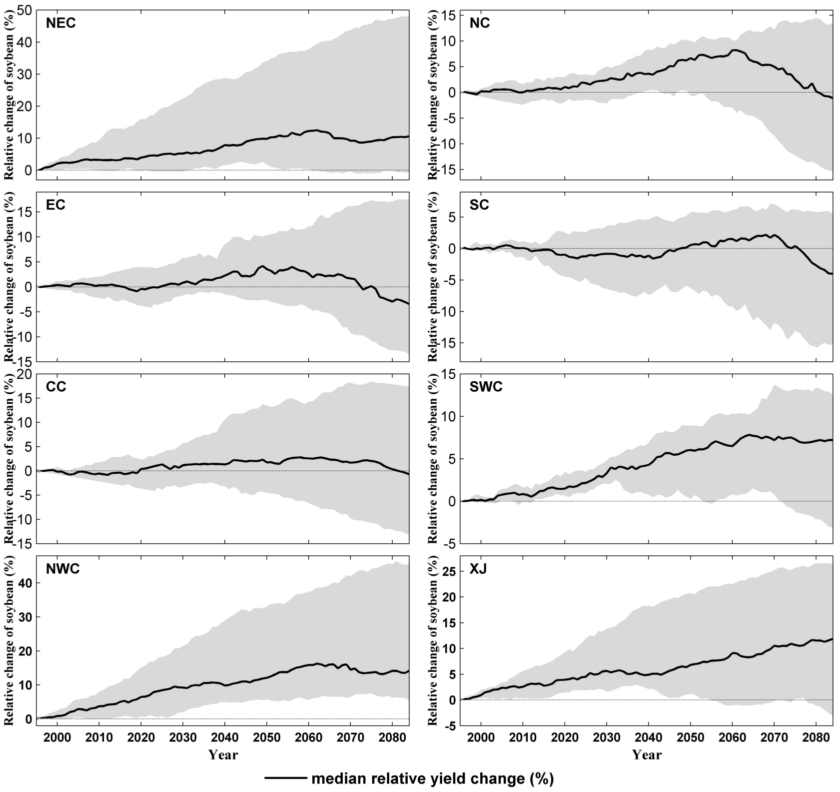

Figure 6. The relative change of the simulated soybean yield at the regions of China. The MMs and the 25th and 75th percentiles of the model pairs are shown.

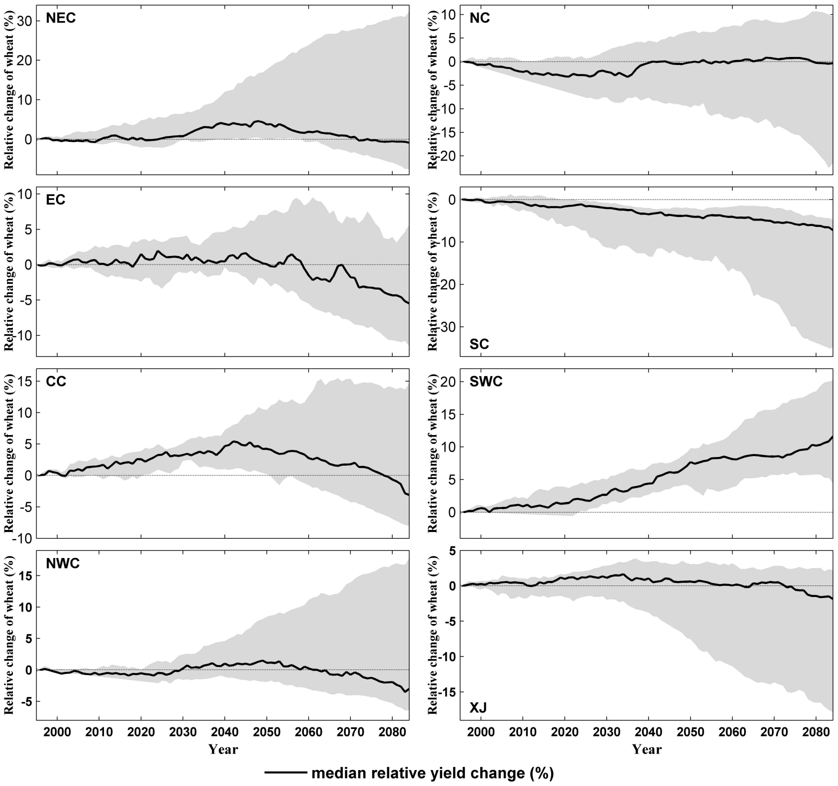

Figure 7. The relative change of the simulated wheat yield at the regions of China. The MMs and the 25th and 75th percentiles of the model pairs are shown.

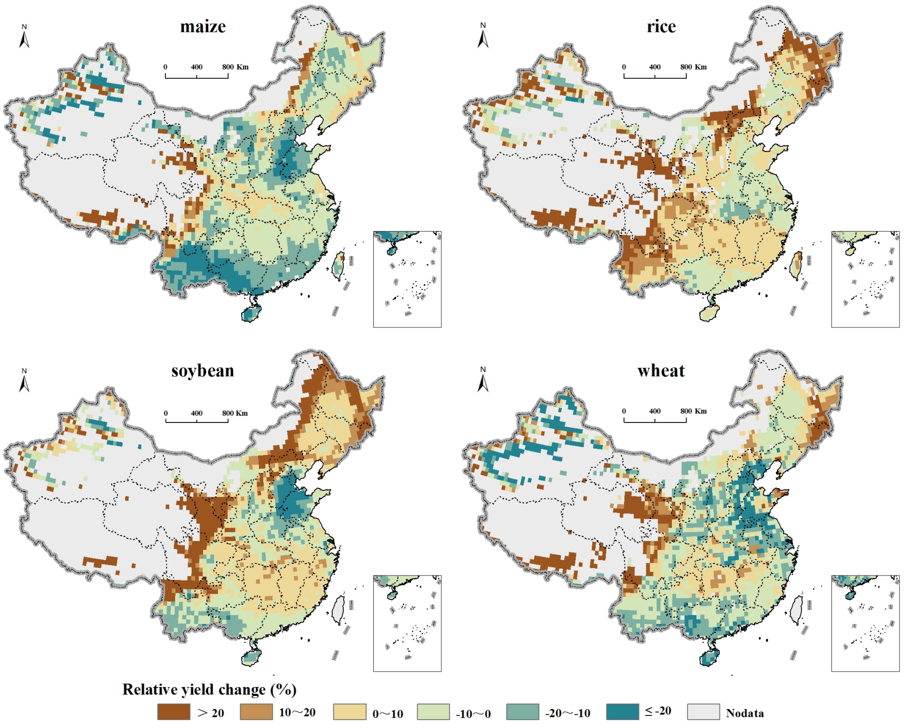

Figure 8. The relative change of the simulated yield of maize **(a)**, rice **(b)**, soybean **(c)**, and wheat **(d)** at the end of the 21st century (2070–2099) comparing with the simulated yield in the historical period (1981–2010).

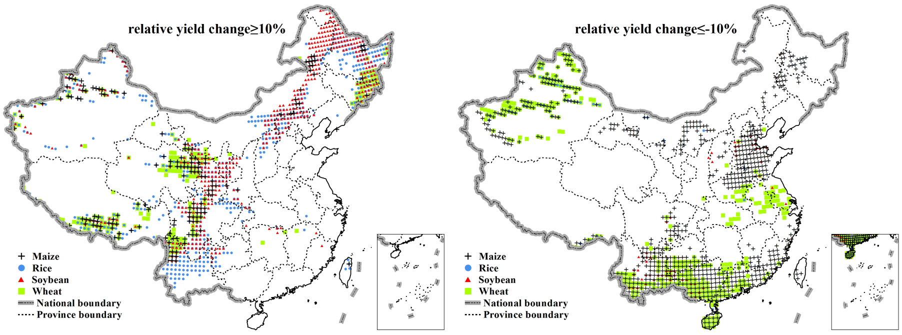

Figure 9. The high climate resilience areas (left panel) and high climate risk areas (right panel) for the major crops in China.