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Potential benefits of climate change for crop productivity in China

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ABSTRACT

Multiple cropping systems are particularly important in China to feed the 19% of the world's population with only 8% of the arable land. Rising temperatures can dramatically affect multiple cropping systems and, as a consequence, food security in China. Here, we investigate the impacts of climate change on the northern limits and crop planting areas of multiple cropping systems in China, and estimate the impacts of the change in the crop planting areas of multiple cropping systems on the China's crop production (maize, wheat, and rice). Based on both historical climate observations from the China Meteorological Administration and future climate A1B emission scenario (IPCC, 2007) data for China, we evaluate the effects of climate change on multiple cropping systems in China. Historical statistical crop yield and simulated crop yield by Agricultural Production Systems Simulator (APSIM model) in 2011–2100 were used to quantify the crop production (maize, wheat, and rice) in China. We found that the northern limits of multiple cropping systems have been shifted northward. The projected area of cultivated land for triple-cropping system may significantly expand during the 21st century. The northern shifts resulted in a 2.2% (~8,000,000 t) increase in national production of three major crops (maize, wheat, and rice) during the period from 1981 to 2010, positively impacting China's food security. Therefore, we conclude that the warming due to climate change may cause a positive impact on the crop production in China if concomitant changes adapted in multiple cropping systems take place.

1. Introduction

Demand for food is rising and will continue to rise with increases in global population and consumption (Godfray et al., 2010). Over the last 50 years (1961–2009), world cropland area grew by only 12 percent with a doubling of world population (FAO, 2012). As a result, global cropland per capita declined from 0.44 ha to less than 0.25 ha, while China experienced a decline from 0.15 ha to 0.08 ha per capita (FAO, 2012). For China, with 19% of the world's population and only 8% of the arable land (FAOSTAT, 2012), food security is an extremely important issue. One aspect of food security is crop production which is composed of the product of three elements: arable land, cropping intensity (the frequency with which crops are harvested from a given area), and yield (FAO, 2002). The product of arable land and the cropping intensity is the crop planting areas. Meeting the need for increased crop productivity will require an increase in one or more of these three factors. Therefore, increasing cropping intensity in order to improve crop productivity is critical for China's food security (FAO, 2002). Benefiting from a monsoon climate, China has long and successfully adapted multiple cropping systems and has one of the highest multiple-cropping index in the world.

During the past few decades, crop yields have increased due to improved crop varieties, crop management, and utilization of fertilizers and irrigation. However, increased temperatures would shorten the crop growth period, possibly reduce yields, and possibly increase yield variability without management adaptation (Sirotenko et al., 1997; Porter and Gawith, 1999; Tubiello et al., 2000; Lobell et al., 2011). These adaptation practices which could

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counteract warming effects include changes in sowing dates (Bassu et al., 2009), use of new crop species and varieties with longer growing season (Olesen et al., 2000; Gao et al., 2003), and changes in cropping systems (IRRI, 1984; FAO, 2002). Some scientists have attempted to quantify the effects of climate change on cropping systems. In Europe, the cropping area of the cooler season and warmer season seed crops will probably expand northwards with warming (Carter et al., 1996; Wolf, 2000). In China, climatic warming led to the westward and northward expansion of both winter wheat (Hao et al., 2001; Yang et al., 2010, 2011; Jin et al., 2002) and rice planting areas (Yun et al., 2005).

The first global assessment of the potential impacts of climate change on crops was conducted in 1994 (Rosenzwelg and Parry, 1994). Since then, there has been increased knowledge of the effects of climate on crop plant physiology, the crop modeling performance has been improved, and quality crop, soil, and climatic datasets have become available. However, there has been little research to be reported for the effects of climate changes on the northern limits of cropping systems in China. We conducted a systematic national evaluation to investigate the crop productivity of changes in China's multiple cropping systems due to climate change. The objectives of this research effort are (i) to quantity the northern limits and crop planting areas of multiple cropping systems during the past six decades as well as the likely effects of climate change in China, and (ii) to estimate the impacts of changes in the northern limits of multiple cropping systems on China's crop production (maize, wheat, and rice).

2. Materials and methods

2.1. Study sites

The study area comprised of all mainland China except for Xinjiang Uygur and Tibet, which are two autonomous regions (Fig. 1). Both autonomous regions only account for less than 0.6% of total crop sown area with only 2.0% of the nation's production (National Bureau of Statistics of China (NBSC), 2000–2010National Bureau of Statistics of China (NBSC), 2000–2010).

2.2. Climate and crop data

The climate data sets used for the study area were of two categories. One category consisted of historical weather data from 546 sites for the period of 1951–2010. The data was obtained from the National Meteorological Network Weather Stations under the China Meteorological Administration (CMA). These sites have been shown in Fig. 1. The second data set consisted of future climate scenarios on a $0.25^\circ \times 0.25^\circ$ geographic grid generated for the period 2011–2100 by the National Climate Center (NCC) in China. The outputs were generated using the Global Climate Model (GCM) and Regional Climate Model (RegCM3) from the Abdus Salam International Centre for Theoretical Physics (ICTP) considering the IPCC SRES A1B scenarios (Giorgi and Mearns, 2003; Xu et al., 2010).

The experiment data on maize phenology, aboveground dry matter, yields, and management practices were obtained from the local agricultural meteorological experimental stations. These observations have been taken following uniform CMA observing standards and guidelines for monitoring surface climate, phenology, and crop yield data across the country. The hybrids used in the experiment stations were higher yielding hybrids (Liu et al., 2012) in contrast to on-farm hybrids. In this study, we selected the most popularly cultivated variety for representing each crop on the selected experimental stations. The crop varieties and selected experimental stations used for model's calibrations are given in Table S1 in Supporting information. The APSIM model was calibrated with the yield data from the experimental stations.

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The annual wheat, maize, and rice total yield data for each province from 1951 to 2010 were taken from the National Bureau of Statistics of China (NBSC), which is essentially collected by local investigators. These statistical data were used as baselines and were compared with the total yields to verify any change in the cropping systems in China.

2.3. Analysis of the shifts of northern limits for multiple cropping systems

Liu and Han (1987) had accomplished the classifications of multiple cropping systems in China in the mid-1980s. The indices they used for multiple cropping systems (single-cropping, double-cropping and triple-cropping) are given in Table 1. The most applicable index used in China is the annual accumulated temperature above 0 °C (AAT0). It is calculated as the summation of the daily average air temperatures (T_i on day i) above the baseline temperature (T_b) of 0 °C for the period with T_i steadily above 0 °C ($GP_{t=0}$) (Fischer et al., 2002). The AAT0 is calculated as:

$$\mathrm{AAT0} = \sum_{i=a}^{b} T_i \quad T_i \geq 0 \tag{1}$$

where a and b are the starting and ending dates of $GP_{t=0}$, respectively. For each station or grid point and each year, the thermal summation method used by Liu and Han (1987) was selected to determine the starting and ending date of $GP_{t=0}$ in each year. The thermal summation between T_i and T_b (here T_b is 0 °C) were calculated in a daily step starting from a day when T_i first reaches to 0 °C. If $T_i - T_b > 0$, the thermal summation is positive value, otherwise it is negative. The sum of positive and negative values is calculated consecutively. The starting date of $GP_{t=0}$ in each year is defined as the first day whenever the absolute sum of the positive values is twice as large as the absolute sum of negative values. Similarly, the ending date is defined as the last day whenever the absolute sum of the negative values is twice as large as the absolute sum of positive values (Qu, 1991).

In our study, the period from 1951 to 1980 years were selected as the baseline to compare the northern limits for multiple cropping systems with the period of 1981–2010. This allowed us to examine the historical changes in multiple cropping systems relative to the baseline period. Similarly, we selected 1981–2010 as another baseline period to compare northern limits for multiple cropping systems during 2011–2040 (2020s) and 2071–2100 (2080s), to predict the likely changes in the future 30 years and the last 30 years of 21st century. For each period we calculated, we ranked the calculated AAT0 from the lowest to the highest. After accounting for the impacts of climate variability on the AAT0 and actual agricultural production we chose the 20th percentile AAT0 value as an indicator for thermal conditions above temperature of 0 °C during the four periods (1951–1980, 1981–2010, 2020s, and 2080s) for each grid or individual stations. On the other hand, we evaluated the impact of climate variability on the northern limits of multiple cropping systems. The area between northern-most and southern-most lines of these 30 lines was considered as the change of the northern limits from year to year caused by climate variabilities.

2.4. APSIM model and simulation

The Agricultural Production Systems Simulator (APSIM) developed by the Agricultural Production Systems Research Unit in

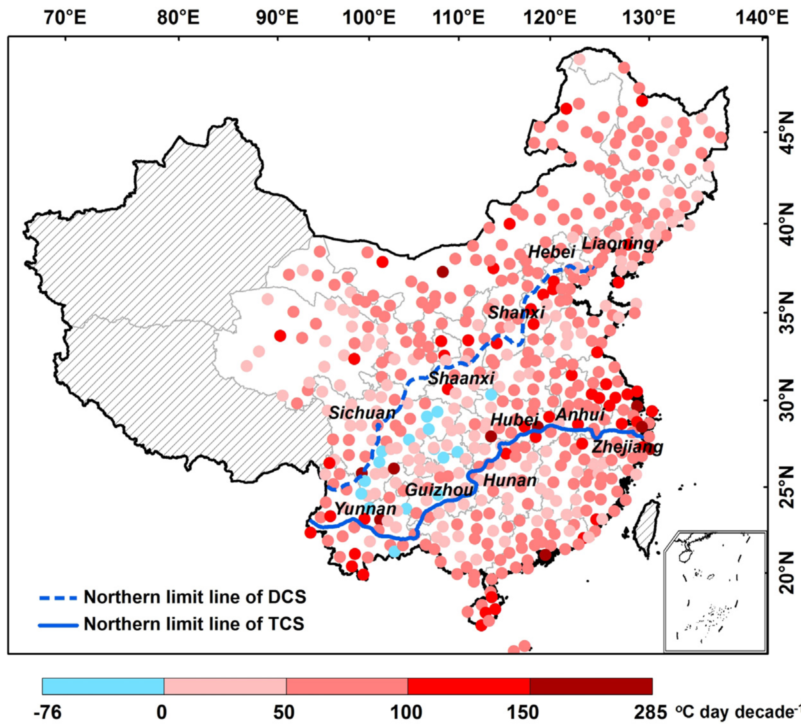

Fig. 1. Northern limits of China's cropping systems for the double-cropping system (DCS, dash line) and triple-cropping system (TCS, solid line) developed and adapted in early 1980s. Dots represent the climate/weather stations colored with trends of mean accumulated temperature above 0 °C (°C day per decade) in China from 1961–2010.

Australia, has been proven to be an effective tool to investigate the potential impacts of climate change on crop productivity (Keating et al., 2003; Liu et al., 2010). The APSIM model has also been calibrated and used for simulating the growth and yield of maize and wheat in North China Plain (Wang et al., 2007; Li et al., 2009; Chen et al., 2010), maize in Northeast China (Liu et al., 2012), and rice in middle and lower reaches of Yangtze River, China and aerobic rice in North China Plain (Xue et al., 2007; Zhang et al., 2007; Shuai et al., 2009). The APSIM-Maize model was initially calibrated for spring and summer maize cultivar parameters by adjusting various parameters, thermal time required from emergence to end of juvenile stage and from flowering to maturity, maximum grain numbers per head and grain-filling rate. Similarly, in case of APSIM-Wheat model, the calibration of winter wheat cultivar parameters was also done by adjusting modeling parameters including sensitivity to vernalization, sensitivity to photoperiod, thermal time from the beginning of grain-filling to the maturity, and coefficients of kernel number per stem weight at the beginning of grain-filling and potential grain-filling rate. All APSIM models were calibrated and validated using the data described in the Table S1. As a part of this study, calibration and validation were also conducted for the parameters of double-rice (early rice and late rice) and single rice in APSIM-ORYZA based on the datasets from experimental station in middle and lower reaches of Yangtze River in China, as described in the Table S1. These parameters are development rates, assimilation partitioning factors, specific leaf area, relative leaf growth rate, leaf death rate, fraction of stem reserves, and maximum grain weight (Bouman & van Laar, 2006).

After calibrations, APSIM models were run by using gridded climate data (2011–2100) to quantify the yields of maize, wheat, and rice in the provinces with the multiple cropping systems. The simulated crop was sown on the fixed date in each period in 2011–2040 and 2071–2100. Based on the average of the actual sowing dates from the agricultural experimental stations in the areas of northern limits for the double-cropping systems, the winter wheat and summer maize were sown on 26 September and 23 June every year from 1981 to 2010, respectively. Previous studies had indicated that delay of the sowing time of winter wheat in North China will significantly increase crop yield (Wang et al., 2012). Therefore, we delayed the sowing date of winter wheat during the period from 2011 to 2040 and 2071 to 2100. Spring maize was sown on the 30-year average of starting date of $GP_{t=0}$ in each grid during the period from 2011 to 2040 and 2071 to 2100. Based on the average of the actual sowing dates from the experimental stations in each province, the single rice was sown on 5 May, 10 May, and 20 May every year from 1981 to 2010 in Hubei, Anhui, and Jiangsu province, respectively. Earlier studies have reported that single rice can provide more stable yield if the sowing date was delayed because the crop will get sufficient thermal conditions and simultaneously avoid the hot weather damages (Zhao, 2006). Therefore, in our study, the sowing date of single rice in 2011–2040 and 2071–2100, was delayed by 10 days compared to that in 1981–2010 (Shi et al., 2001). Because of lacking the actual sowing data of early and late rice, early rice was sown on the 30-year average date in each grid (Gao and Li, 1992) and late rice was sown 30 days prior to the maturity of early rice. To eliminate the

Table 1
Indices for multiple cropping systems in China.

Cropping system	AAT0 (°C day)	Extreme minimum temperature (°C)	Period of 20 °C termination
Single-cropping	<4000–4200	<−20	Early August–early September
Double-cropping	>4000–4200	>−20	Early September–beginning in late September
Triple-cropping	>5900–6100	>−20	Beginning in late September–early November

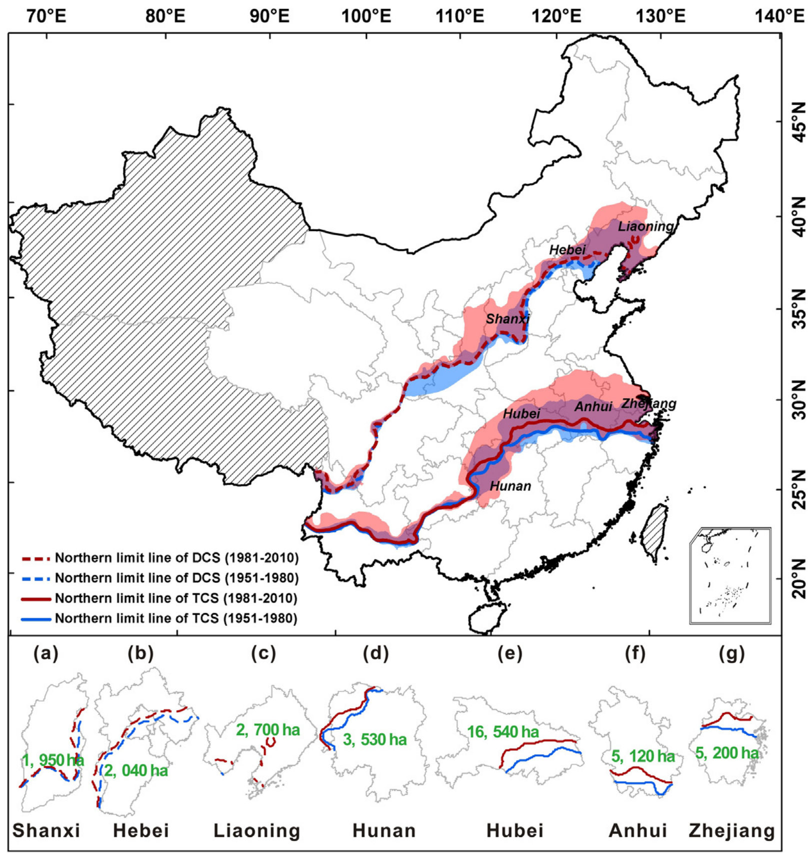

Fig. 2. Changes of northern limits for double-cropping system (DCS) and triple-cropping system (TCS) in China from the period of 1951–1980 (line in the relatively south) to the 1981–2010 (line in the relatively north). The shading areas indicate ranges of northern limit lines during the period from 1951 to 1980, and 1981 to 2010, respectively, due to year-to-year variation. The bottom panel shows enlarged shifts for seven provinces of Shanxi (A), Hebei (B), Liaoning (C), Hunan (D), Hubei (E), Anhui (F), and Zhejiang (G) shown in the top panel. The numbers shown in (A) to (G) indicate changes of arable land acreages between the 1951–1980 and the 1981–2010.

impact of varietal changes, a single variety was utilized at each grid for the entire period. Water applications were set equal to the water use of the crop and nutrient inputs were taken as non-limiting in order to eliminate the effect of water and nutrient stresses on simulated yield. Planting density, sowing depth, and other management details are based on the data from the agricultural experimental stations and kept constant throughout the simulation period.

2.5. Analysis of yield difference

During the yield analysis and yield difference computation, we have following assumptions:

a The total planting areas and regional planting acreage distribution remained unchanged during each specific study period,
b All changed arable land areas caused by changes of multiple cropping systems were used to plant grain crops.

Because the cropping rotations were occasionally varied in an irregular temporal span, we selected the most representative planting rotations to show the effects of planting northern limits on the yields. When we analyzed the impacts of cropping system changes on yield, from single-cropping to double-cropping, spring maize was selected as the most representative planting pattern for single-cropping, and winter wheat–summer maize was selected to be the most representative planting pattern for double-cropping system. When analyzing the impacts of changes of multiple cropping systems, from the double-cropping to triple-cropping on yield, winter wheat–single rice was selected to be the representative planting pattern for double-cropping, and winter wheat–early rice–late rice was the most representative planting pattern for triple-cropping system.

To estimate the national crop production difference, for the provinces where multiple cropping systems were not changed, we used actual yield from National Bureau of Statistics of China (NBSC) from 1951 to 2010, and took the results of future (2020s and 2080s) crop yields in China available under A2 emission scenario (Ju et al., 2005; Xiong et al., 2005, 2008). But the impact of climate change on crop yields in China under A1B and A2 emission scenario was similar (Müller et al., 2012). For those provinces, where cropping system may change, we only calculated the production changes occurred between two northern limit lines. It was calculated by using the changes of planting areas and simulated crop yields by APSIM.

3. Results

3.1. Effects of climate change on the northern limits of multiple cropping systems in China

China's multiple cropping systems can be divided into three types: single-cropping system (SCS), double-cropping system (DCS), and triple-cropping system (TCS) (Fig. 1). The SCS is the main cropping system in high-latitude areas in northern China and hilly arid areas in southwest China. The DCS is prevalent in northern China, southwest China, the middle and low reaches of the Yangtze River, and the hilly area in southeast China. The northern limits of TCS transect multiple provinces including Yunnan, Guizhou, Hunan, Hubei, Anhui, and Zhejiang (Fig. 1).

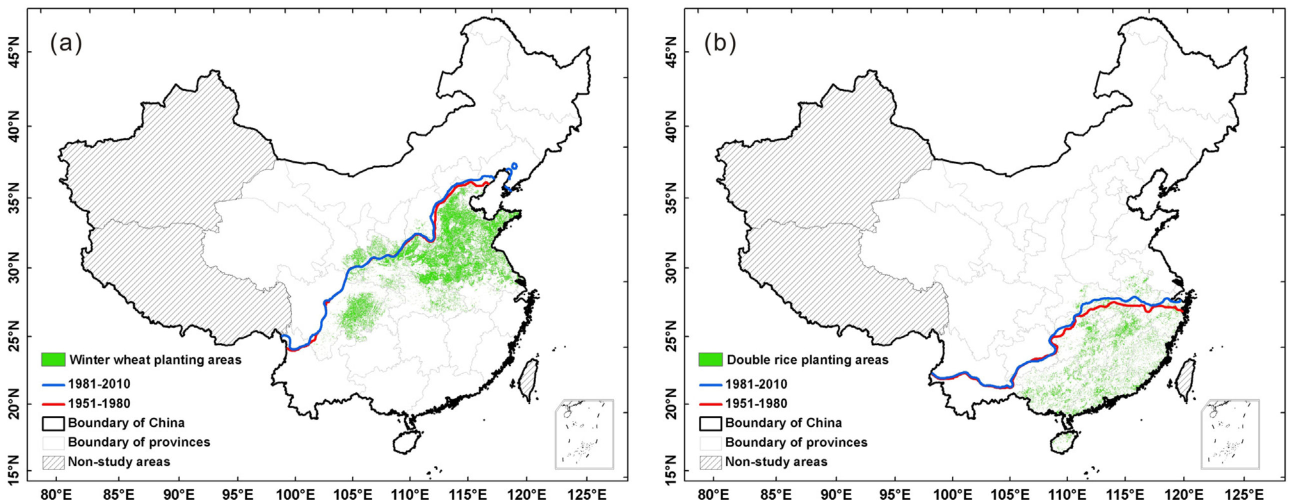

Fig. 3. The actual planting areas for winter wheat (a) and double rice (b) in 2010.

Previous studies have indicated that China experienced a significant increase of mean air temperatures (IPCC, 2007; Dong et al., 2009). Our results indicated that annual accumulated temperature above 0 °C (AAT0, see detail definition and calculation procedures in Section 2) in China has increased during the period from 1961 to 2010. On average, mean AAT0 increased 64.4 °C day per decade, and 90% of the locations significantly increased in 0–100 °C day per decade (Fig. 1).

Compared to the period from 1951 to 1980, our results indicate that the northern limits of DCS moved northward and westward

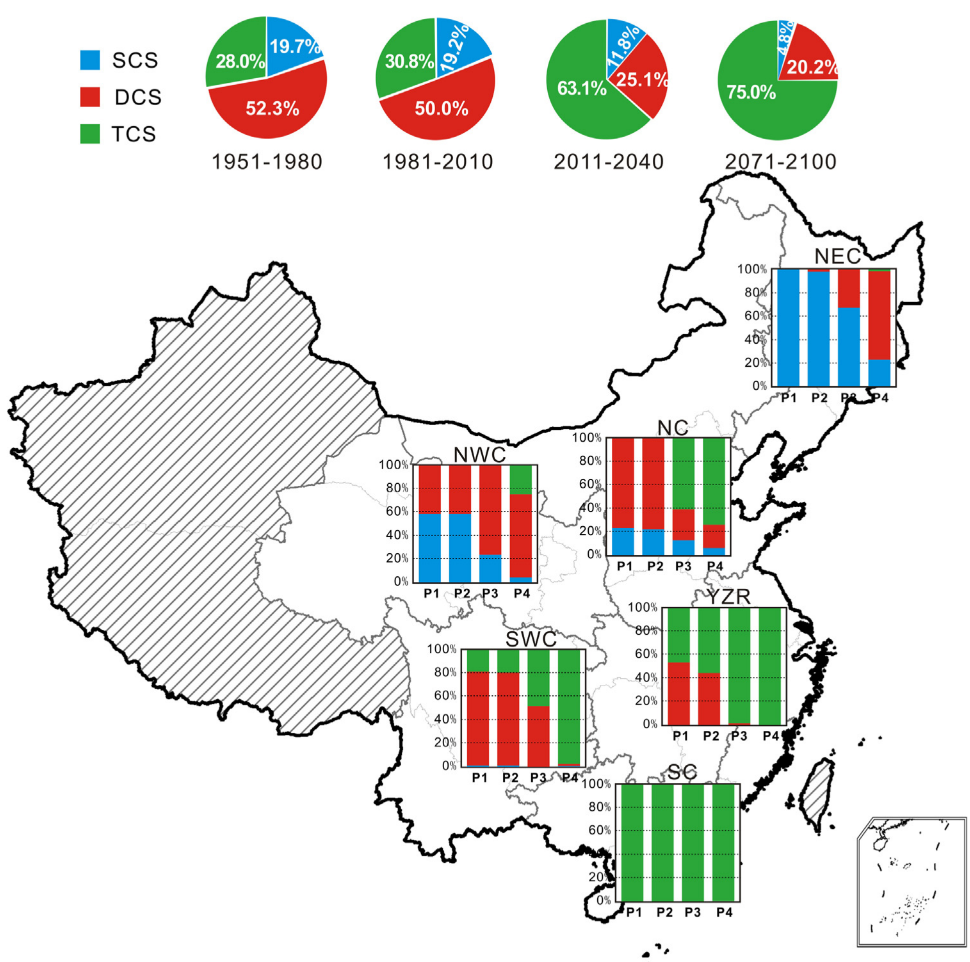

Fig. 4. Percentages of crop planting areas (%) for multiple cropping systems during 1951–1980 (P1), 1981–2010 (P2), 2011–2040 (P3), and 2071–2100 (P4) in six agricultural regions: northeast China (NEC), northern China (NC), northwest China (NWC), middle and lower reaches of Yangtze River (YZR), southwest China (SWC), and southern China (SC). The pie charts on the top panel indicate percentages of crop planting areas (%) for single-cropping system (SCS), double-cropping system (DCS), and triple-cropping system (TCS) during 1951–1980, 1981–2010, 2011–2040, and 2071–2100 in China, respectively.

during the period from 1981 to 2010 (Fig. 2), especially in northeast China (Liaoning province) and northern China (Hebei and Shanxi provinces). The northern limits have been moved around 70 km, 30 km, and 20 km northward in the provinces of Liaoning, Hebei, and Shanxi, respectively, for the DCS. Likewise, the northern limits of TCS in the middle and lower reaches of Yangtze River (provinces of Zhejiang, Anhui, Hubei, and Hunan) moved around 70 km northward (Fig. 2). The increases of arable land acreage for TCS, as an example of Hubei province, are up to 16,540 ha (i.e., crop planting areas = 3 × 16,540 ha), which is the largest increase of TCS for a single province in China. It should be noted that if considering heat resources in each individual year, the northern limits of multiple cropping systems varied year by year due to the climate variability during the period of 1981–2010 (Fig. 2).

As we have mentioned in the Section 2, when we analyzed the cropping systems changing from SCS to DCS, spring maize, and winter wheat-summer maize were selected as the most representative planting patterns for SCS and DCS, respectively. When analyzing the cropping systems changing from DCS to TCS, winter wheat-single rice, and winter wheat-early rice-late rice (double rice) were selected to be the representative planting patterns for DCS and TCS, respectively. Therefore, to examine whether local farmers have adapted climate change impact on China's multiple cropping systems during recent years, we used actual winter wheat and double rice planting areas in 2010 to demonstrate these adaptations (Fig. 3). In Fig. 3a, around the northern limits of DCS, winter wheat have already applied in these locations, which indicates that local climate provides enough heat resources for DCS in 2010. The similar results were also found in the northern limits of TCS.

Due to the increasing of AAT0 (Fig. S1), the projected northern limits for DCS and TCS are further shifted northward (Fig. S2) in China during the 2020s and 2080s. The northern limits of DCS have been moved around 480 km, 50 km, 80 km, and 420 km northward in the provinces of Liaoning, Hebei, Shanxi, and Shaanxi during the 2020s, and moved about 870 km, 120 km, 180 km, and 670 km northward during the 2080s, respectively. Likewise, the northern limits of TCS moved around 590 km, 930 km, 520 km, 90 km, 240 km, 170 km northward in the provinces of Zhejiang, Anhui, Hubei, Hunan, Guizhou, and Yunnan during 2020s (Fig. S2). The northern limits of TCS in 2080s would closely reach the northern limits of DCS in 1951–1980. Such a significant northern expansion of TCS would provide great potentials of food security in China but also the revolutionary challenges for water and environment

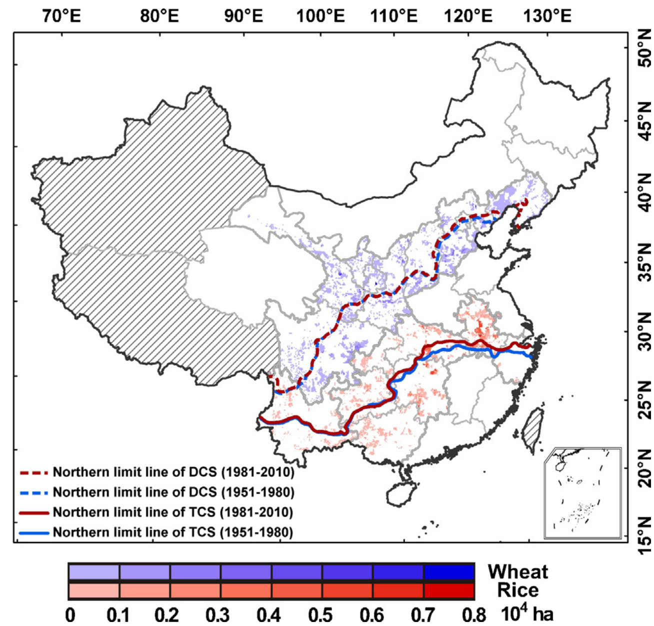

Fig. 5. The increases of actual planting areas for wheat (dots around the northern limits of DCS) and rice (dots around the northern limits of TCS) between 1980 and 2010, which indicates an increase of planting areas for wheat and rice when compared to 1980.

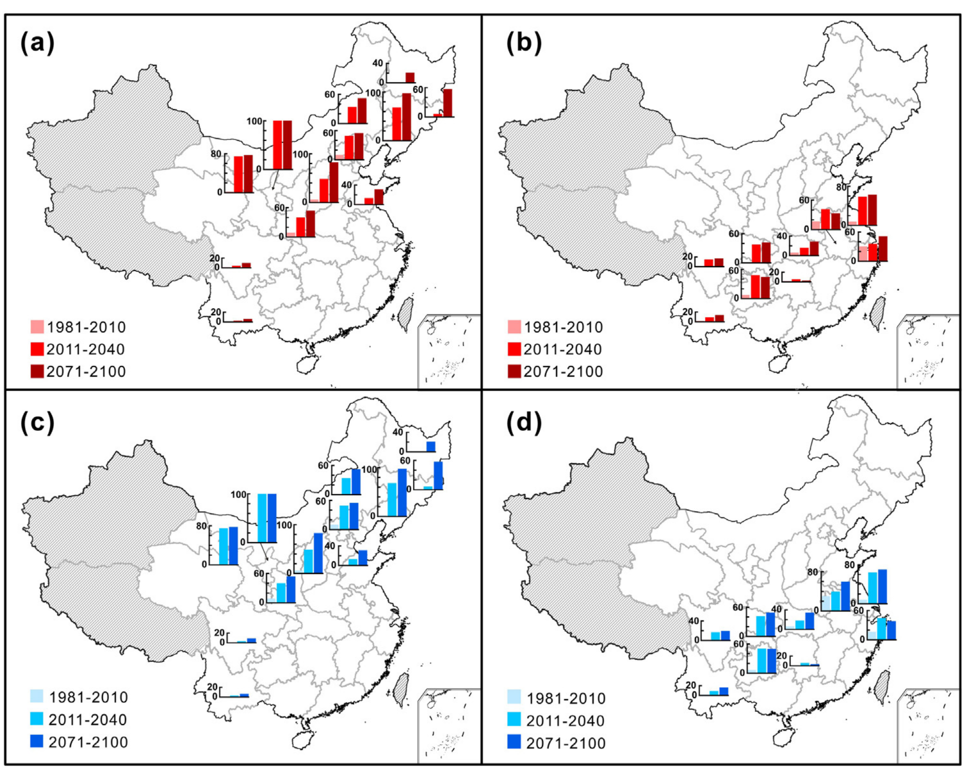

Fig. 6. Changes of crop production for wheat (A and C) and rice (B and D) in percentage (%) due to changes of cropping systems without CO_2-fertilization effect (A and B) and with CO_2-fertilization effect (C and D) during 1981–2010, 2011–2040, and 2071–2100.

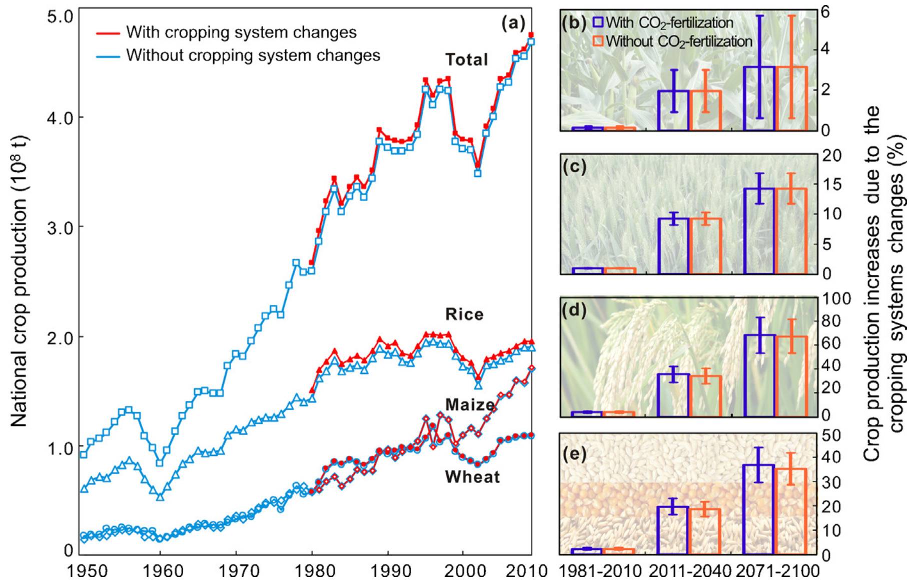

Fig. 7. National crop production of maize (◊), wheat (◯), rice (△), and their total (□) due to changes of cropping systems (a) during 1951–2010. The bar charts on the right indicate crop production increases (%) of maize (b), wheat (c), rice (d), and their total (e) due to the cropping system changing under conditions of with CO_2-fertilization effect and without CO_2-fertilization effect during 1981–2010, 2011–2040, and 2071–2100 in China.

resources. In contrast to the projected results, under the scenarios of 1 °C, 2 °C, 3 °C, and 6 °C temperature increases, the northern limits of multiple cropping systems would significantly move northward (Fig. S3), which reflects a national cropping system change similar to the projected scenario in current century.

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3.2. Effects of climate change on the planting areas of multiple cropping systems in China

During 1951–1980, crop planting areas of these three cropping systems, SCS, DCS, and TCS, accounted for 19.7%, 52.3%, and 28.0% of the study region's total crop planting area (Fig. 4), respectively. As a consequence of multiple cropping systems changes, the percentage of crop planting area for SCS were reduced from 19.7% during the period from 1951 to 1980 to 19.2% during the period from 1981 to 2010, equivalent to about 8200 ha crop planting area decreased, and from 52.3% to 50.0% for DCS, equivalent to about 49,900 ha crop planting area decreased. However, the planting area for TCS increased from 28.0% during the period from 1951 to 1980 to 30.8% during the period from 1981 to 2010, which corresponds to an increase of about 98,500 ha (Fig. 4). To examine whether local farmers have adapted climate change impact on China's multiple cropping systems during recent years, we used actual crop planting data in China to demonstrate these adaptations in terms of changing cropping systems (Fig. 5). As examples, both wheat and rice planting areas surrounding 1951–1980 northern limit and 1981–2010 northern limits have been increased (Fig. 5). The projected China's crop planting areas for single- and double-cropping would decrease and crop planting areas for triple-cropping system would significantly increase (Fig. S4).

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3.3. Effects of multiple cropping system changes on crop production in China

The increase of temperature has resulted in the northern limits of multiple cropping systems moving northward. In our analysis, it was assumed that spring maize was replaced by a winter wheat-summer maize rotation in the areas where cropping system switched from SCS to DCS. In the areas where cropping system switched from DCS to TCS, a winter wheat-single rice rotation was replaced by winter wheat-early rice-late rice rotation. Consequently, multiple cropping systems' changes lead to a projected increase of crop production, especially for wheat and rice (Fig. 6). During 1981–2010, national total production of maize, wheat, and rice increased by 0.1%, 0.9%, and 4.0%, respectively, given the relative changes of multiple cropping systems. The largest changes 4.0% in rice production is obviously caused by increases of rice planting areas due to expanding northern limited for both DCS and TCS. National total production of three major crops (maize, wheat, and rice) in China increased by 2.2% (~8,000,000 t) if multiple cropping systems' changes take place (Fig. 7).

Under the A1B scenario, if these changes of multiple cropping systems were applied, national production of maize, wheat, and rice during the 2020s would be projected to increase by 2.0%, 9.2%, and 34.0%, respectively, without considering CO_2-fertilization effect in crop simulation. And during 2080s, projected national production of maize, wheat, and rice would increase by 3.2%, 14.2%, and 67.4%, respectively. The projected national production of three major crops (maize, wheat, and rice) in China during 2020s and 2080s would increase by 18.6%, and 35.2%, respectively, with these changes of multiple cropping systems (Fig. 7). In addition to rising CO_2, a number of environmental and biotic factors could cause the changes of crop productions. Our results indicated that projected crop production would increase by 19.7% and 36.8%, respectively, during 2020s and 2080s (Fig. 7).

4. Discussion

To examine whether local farmers have adapted climate change impact on China's multiple cropping systems during recent years, we used actual crop planting data in China to demonstrate these adaptations in terms of changing cropping systems (Figs. 3 and 5). In addition to the DCS and TCS adaptations, the rice planting in Heilongjiang province (northeast China) has been expanded from 0.22 Mha in 1980s to 2.25 Mha in 2007 according to Chinese National Bureau of Statistics (Piao et al., 2010). Although such local adaptations illustrated cropping system's changes in China the systematic and strategic adaptation plans have not been well initiated yet. Whether these changes of cropping systems could take place is still uncertain due to the combinations of various constraint factors such as economic, social, and environmental benefits, as well as farmer acceptance. In addition, crop breeding is an important adaptive response to climate change through the use of genetic techniques, such as heat stress resistant and drought tolerant varieties. Collections of genetic resources may be screened to find sources of resistance to changing diseases and insects, as well as tolerances to heat and water stress and better compatibility to new agricultural technologies (Olesen and Bindi, 2002).

There is increasing evidence of stagnation in crop yield potential as measured under optimal growing conditions (Duvick and Cassman, 1999; Peng et al., 1999). According to the National Bureau of Statistics of China, the entire country lost around 12.4 million hectares of arable land between 1980 and 2008. Therefore, increasing cropping intensity via multiple cropping systems may be an effective way to feed an increasing population in China. Our results indicate that China's crop production will benefit from the increasing crop planting areas for both double- and triple-cropping systems. However, under the influence of climate change, the northern expansion of the triple-cropping system could make more multiple-cropping system's crop areas exposed to relatively larger climate variability located in northern areas in China. In this context, extreme weather events may become more frequent and more damaging to multiple crop systems. Therefore, further adaptation measures on the impacts of weather and climate extremes are also important in future in China's multiple cropping systems. In this paper, we simulated the yield changing for three major crops in the areas with multiple cropping systems with irrigation. However, the North China Plain has long relied on groundwater to irrigate crops, and over-pumping groundwater has caused groundwater levels persistently declining at a rate of 1 m year^{-1} on average (Hu et al., 2005). A 2.2% of national total production increase of three major crops (maize, wheat, and rice) in China during 1981–2010 requires more water resources, thus more irrigation may jeopardize the local agricultural development in the long run.

The scenario analysis in our study provides a foundation toward understanding the impacts in China's crop productivity today and into the future through adapting China's cropping systems. There is no simple solution to sustainably feed increased population, especially for foreseeable increase of urbanization in China. Getting better evidence toward potential benefits of climate change impacts will help some extent to increase the crop productivity in China. Society has an opportunity now to make adaptations with tremendous implications for future sustainability and food security.

5. Conclusion

We assessed the effects of climate change on the northern limits and crop planting areas of multiple cropping systems in China based on both historical climate observations and future climate A1B emission scenario (IPCC, 2007) data; then we used historical statistical crop yield and simulated crop yield by Agricultural Production Systems Simulator (APSIM model) in 2011–2100 to quantify the impacts of changes in the northern limits of multiple cropping systems on China's crop production (maize, wheat, and rice). We found that the northern limits of multiple cropping systems have been shifted northward. The projected China's crop planting areas for single- and double-cropping systems would decrease and crop planting areas for triple-cropping system would significantly expand during the 21st century. The northern shifts of multiple cropping systems resulted in a 2.2% (~8,000,000 t) increase in national production of three major crops (maize, wheat, and rice) during the period from 1981 to 2010, which indicated warming due to climate change may cause a positive impact on the crop production in China if concomitant changes adapted in multiple cropping systems take place.

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