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Impacts of climate change on growth period and planting boundaries of winter wheat in China under RCP4.5 scenario

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Abstract

This paper advances understanding of the impacts of climate change on crops in China by moving from ex-post analysis to forecasting, and by demonstrating how the effects of climate change will affect the growth period and the planting boundaries of winter wheat. Using a multiple regression model based on agricultural meteorological observations and the IPCC AR5 GCMs simulations, we find that the sowing date of winter wheat in the base period, 2040s and 2070s, shows a gradually delayed trend from north to south and the growth period of winter wheat in China will be shortened under climate change. The simulation results also show that (i) the north planting boundaries of winter wheat in China will likely move northward and expand westward in the future, while the south planting boundary will rise and spread in south Hainan and Taiwan; and (ii) the Xinjiang Uygur Autonomous Region and the Inner Mongolia Autonomous Region will have the largest increases in planting areas in 2040s and 2070s. Our simulation implies that Xinjiang and Inner Mongolia are more sensitive to climate change than other regions in China and priority should be given to design adaptation strategies for winter wheat planting for these provinces.

1 Introduction

According to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change, IPCC AR5, the period from 1983 to 2012 was likely the warmest 30 year period of the last 1400 years in the Northern Hemisphere (IPCC, 2013). Climate change directly affects the temporal and spatial distribution of the basic agricultural production elements (light, water and heat conditions) (Sun et al., 2005; Phillips and Gleckler, 2006; Tubiello et al., 2007; Tan et al., 2013), and it is widely regarded as having important implications for world food security and agricultural sustainable development (Jin et al., 1994; Wang et al., 2009; Yao et al., 2011). Thus, agriculture is one of the most vulnerable sectors under climate change (Tubiello et al., 2007; Tan et al., 2013), especially in China, the world's largest developing economy. While projecting future impacts of climate change on agriculture has become increasingly important in China, the literature has rarely used rigorous methodologies and high quality data to take China's climate policy one step forward (Chen et al., 2015).

Most previous studies on investigating the impacts of climate change on agricultural production have used three main research methods. First, researchers interested in the laboratory simulation or field observation experiment (Irigoyen et al., 2014) have used environmental control experiments, such as CO_2 concentration, temperature and moisture, etc., in enclosed chambers (Ziska and Bunce, 1995; Wang et al., 2015), open top chambers (Kellomaki and Wang, 1997), gradient tunnels (Alonso et al., 2008; Venkata-Sreeharsha et al., 2015), or free air (Rosenthal et al., 2014) to assess the future impact of climate change on crops. While this research method can be used to test assumptions or causality assessments, the limitations of spatial and temporal scales as well as the complexity of the experiment design means that the method is not suitable for large scale areas (Li and Chen, 1999; Sun et al., 2007). Second, researchers interested in historically similarity method or analogical method have sought to project the future impacts of climate change on crops by using similar climate conditions observed in the past (Han et al., 2004). However, this approach is not rigorous and may not tell us much about the impacts of climate change on crops over the coming decades.

Finally, other researchers have used numerical and simulation methods. These studies assessed the impacts of climate change on agricultural productivity based on the unified assumption, long time sequence observations, and projections by using Global Climate Models (GCMs). Specifically, the unified assumption is only suitable for small range areas (Cong et al., 2008), and if it is used in large areas, the assumption will be contrary to the basic law of regional diversity. There are also many research reports about the effects of climate change on growth period (Duan and Niu, 2007; Li et al., 2008; Yang, J. Y. et al., 2011; Chen et al., 2012, 2014), planting layout (Wang et al., 2012; Li et al., 2013; Ye et al., 2014), climate suitability (He and Zhou, 2012; Zhu et al., 2012) and yield (Chen et al., 2012, 2014; Zhou et al., 2014) etc., based on long time observations. Although this method can help us understand the impacts of climate change on crops in the past, it cannot project the long-term changes in the future. Nevertheless, the GCM is the major tool for simulating long-term effects of climate change on crops under different scenarios. We contribute to the third part of this research methodology in the literature. In contrast to the vast literature on the effects of climate change on crop yield (Tu et al., 2010; Bocchiola et al., 2013; Hu and Liu, 2013), cropping system (Jin et al., 1994; Wang, 1997; Zhao et al., 2010; Yang, X. G. et al., 2011, 2015) and water use (Cong et al., 2010) simulated by GCMS, there are few studies on how the effects of climate change will affect the growth period and the planting boundaries of crops. This paper fills this gap by choosing the simulations of the GCMs developed by the CMIP5 as the climate change condition, combined with the agricultural meteorological observations, to study the effects of climate change on crops in China. Compared to the CMIP4 (Coupled Model Intercomparison Project Phase 4), the CMIP5 is found to have a higher spatial resolution, a better representation of the dynamical framework and the physical process with more perfect parameterization schemes to advance our knowledge of climate variability and climate change (Chao et al., 2014; Huang et al., 2014). Therefore, we use the CMIP5 and focus on winter wheat, because (1) it plays a major role in crop production and food security in China; (2) the distribution of winter wheat across the nation is wide with different regional varieties of winter wheat (Cheng, 1991; Jiang, 2008); (3) the climate and ecological conditions are diverse and complex; and (4) there exists north planting boundaries and a south boundary of winter wheat will rise in the future (China Crop Climatic Division Cooperation Group, 1987; Jin et al., 1994).

Existing studies in this area is primarily of ex-post nature, however. That is, most empirical analysis uses climate conditions of the long time sequence observations to understand the historical impacts of climate change on winter wheat production. Few studies have assessed the effects of climate change on winter wheat planting boundary under RCP4.5, the latest climate scenarios. Both Hao et al. (2001) and Ji et al. (2003) found that the north safe planting boundary in Liaoning Province in the 1990s extends to about 42.5° N compared with the previously determined boundary (along the Great Wall), and has moved northward by 1 ~ 2 latitude. Li and Che (2005) pointed out that the planting boundary in Hebei Province in the 1990s extends to 41° N compared with the 1950s, and has moved northward by 30 ~ 50 km. It is important to note that in Western China, the Xinjiang Uygur Autonomous Region has formed a stable winter wheat producing area whereas in Gansu province the north planting boundary has moved northward by 50–100 km in the 1990s compared to the 1960s (Deng et al., 2007). While Wang et al. (2012) found that the north planting boundary continually moves northward (Wang et al., 2012), a study by Li et al. (2013) pointed out that the planting boundaries of different winter wheat varieties moves northward significantly, especially the north boundary of the strong winterness. Yet questions remain: compared with the baseline 1996–2005, (1) what is the changed law of the sowing and harvest date of winter wheat in China for the 2040s and the 2070s under RCP4.5?; (2) Will the duration of the growth period be shortened or delayed and what about the spatial distribution of winter wheat?; (3) how will the planting boundary move in the future?; (4) how will the suitable planting region change?; and (5) how will the planting boundaries of winter wheat varieties move in the future? We believe that answering these questions and advancing research in this area requires moving from ex-post models to forecasting.

Therefore, in this paper, we construct a multiple regression model based on agricultural meteorological observations and the IPCC AR5 GCMs simulations, to simulate the spatial distribution of winter wheat growth period in China. We then analyze the effects of climate change on growth periods, possible planting boundaries, the divisions of suitable planting region and the boundaries of winter-spring varieties of winter wheat in China for the base period, 2040s and 2070s, under RCP4.5 scenario. This provides information on the selection of wheat varieties and the optimization of the layout of winter wheat for policy-makers.

2 Material and method

2.1 Data source

The CMIP5 historical simulation test (1850–2005) simulates historical climate evolution process by driving climate model with two factors; external forcing factors, including anthropogenic activities such as greenhouse gas emission, sulphate aerosol and land use; and natural factors such as volcanic aerosol, sea-salt aerosol, ozone and solar radiation (Zhu et al., 2013; Huang et al., 2014). At present, there are uncertainties associated with historical simulation models and data. The limited human understanding of the climate system, the structure of climate models and model parameterization are the major uncertainties for historical simulation (Challinor et al., 2009; Shen and Wang, 2013; Wang et al., 2013; Qin et al., 2014). The uncertainty in future predictions is also largely attributed to the definition of climate change scenarios (Shen and Wang, 2013; Wang et al., 2013; Qin et al., 2014). To address issues of model uncertainty, the climatic data used in this study was abstracted from the latest version of the Global Climate Model released in 2014 by the IPCC Data Center (IPCC, 2013). The IPCC AR5 for the first time used the Representative Concentration Pathways (RCPs) to represent integrated socioeconomic standards, emissions, and climate scenarios to construct the definite mitigation scenario (IPCC, 2013; Shen and Wang, 2013; Wang et al., 2013; Qin et al., 2014). Four RCP types were identified in the IPCC AR5, namely RCP8.5, RCP6, RCP4.5 and the RCP2.6. Here, we chose the RCP4.5 to present the future climate change scenario because the RCP4.5 has in contrast to other RCP types taken integrated socio-economic and policy conditions into consideration which can better present the future development planning of China (Gao et al., 2014). We also chose the 2040s and the 2070s as the study periods for the scenario analysis because emission concentrations of the three major green house gases and the radiative forcing under the RCP4.5 scenario will reach target level in the 2040s and stabilize at 2070s. We believe this is in line with the development trend of China. However, the RCP4.5 projections are associated with uncertainties resulting from its emphasis on the development of population and economy, the innovation of science and technology and the mitigation effects of human activities, such as governmental policy and non-governmental organizations. All of these factors could contribute to unobservable uncertainty.

Given the uncertainty of the GCMs' daily simulations, we obtained daily observations from 660 meteorological stations located all around China (downloaded from China Meteorological Data Sharing Service System http://cdc.nmic.cn/home.do) to evaluate the precision of the daily average climatic factors simulated by the IPCC AR5 GCMs. The results for the benchmark period (1996–2005) show that the MME (Multi-Model Ensemble) model have better accuracy on simulation of precipitation, average temperature and minimum temperature than single models (Sun et al., 2015, 2016). Therefore, the MME model was selected to simulate the climate background in this research. Moreover, observations of winter wheat growth period were abstracted from the dataset "the growth period of China crops and soil moisture in the field for ten days" provided by the China Meteorological Data Sharing Service System. The data-set includes information on the station number, name and date of the growth period, degree of development, departure, plant height and density.

2.2 Methodology

First, we interpolated the simulation results of various climate models by using the Bilinear Interpolation method. We then obtained the simulation values for each meteorological station and evaluated the precision of the basline period (1996–2005). Second, we compared the interpolation results simulated by the GCMs with the observations at the meteorological stations. Finally, we selected the model with the best accuracy as the climatic background to project the impacts of climate change on winter wheat in China.

2.2.1 Bilinear interpolation

The theory of bilinear interpolation (Zhang, 2004) is as follows: based on the nearest four known points (x_1,y_1,z_1), (x_1,y_2,z_2), (x_2,y_1,z_3), (x_2,y_2,z_4), the value of z located at (x, y) can be calculated by linear interpolation on both x and y direction respectively, which is represented as Eq. (1).

$$
\begin{aligned}
z \approx{} & \frac{(x_2 - x)(y_2 - y)}{(x_2 - x_1)(y_2 - y_1)} z_1 + \frac{(x_2 - x)(y - y_1)}{(x_2 - x_1)(y_2 - y_1)} z_2 \\
& + \frac{(x - x_1)(y_2 - y)}{(x_2 - x_1)(y_2 - y_1)} z_3 + \frac{(x - x_1)(y - y_1)}{(x_2 - x_1)(y_2 - y_1)} z_4
\end{aligned}
\qquad (1)
$$

2.2.2 Multiple stepwise regression

Among the various factors that influence the sowing and harvest date of winter wheat in China (China Crop Climatic Division Cooperation Group, 1987; Jin et al., 1994; Chinese Academy of Agricultural Science, 1999; Jiang, 2008), some factors only have limited effects. Yet these factors need to be eliminated to keep the most notable factors for the multiple stepwise regression (Zhejiang university et al., 2001).

2.2.3 Possible planting boundaries of winter wheat in China

Information on the possible planting boundaries of winter wheat in China mainly comes from one source:

1. North boundary: the restrictions of north possible planting boundary used here were referred to the research done by the China Crop Climatic Division Cooperation Group (1987). They show that the average minimum temperature of the coldest month should be above −15 °C, and the extreme minimum temperature should be between −24 ∼ −22 °C (China Crop Climatic Division Cooperation Group, 1987). Notably, the mortality rate of north boundary is 40–60 %. In

addition, the north boundary is also limited by humidity condition. That is, for non-irrigated regions precipitation during growth period of winter wheat should exceed 50 mm. Moreover, in northern part of Xinjiang province (42.2 ~ 49.3° N, 79.8 ~ 91.6° E), snow pack is critical for winter wheat growth, and the average temperature of January and the yearly extreme minimum temperature should be −10 ~ −9 °C and −26 ~ −22 °C respectively.

2. South Boundary: based on the research work of China Crop Climatic Division Cooperation Group (1987), the south boundary of winter wheat do not exist in China but globally, the south boundary of winter wheat has the average minimum temperature of 20 °C for the coldest month.

$$P_i = \begin{cases} 1, \mathrm{mon1avetmin} \geq -15\,^{\circ}\mathrm{C}\,\&\,t\mathrm{min} \geq -24\,^{\circ}\mathrm{C}\,\&\,\mathrm{mon1avetmin} \leq 20\,^{\circ}\mathrm{C}\,\&\,\mathrm{growthpr} \geq 50 \\ 1, \mathrm{mon1avetair} \geq -10\,^{\circ}\mathrm{C}\,\&\,t\mathrm{min} \geq -26\,^{\circ}\mathrm{C}\,\&\,42.2^{\circ} \leq \mathrm{lon} \leq 49.3^{\circ}\,\&\,79.8^{\circ} \leq lat \leq 91.6^{\circ} \\ 0, \mathrm{mon1avetmin} < -15\,^{\circ}\mathrm{C} \| t\mathrm{min} < -24\,^{\circ}\mathrm{C} \| \mathrm{mon1avetmin} > 20\,^{\circ}\mathrm{C} \| \mathrm{growthpr} < 50 \end{cases} \tag{2}$$

According to Eq. (2), the grids above were assigned with the value of 1, otherwise assigned with 0, with i denoting the number of grids, which is 1052 within China under the resolution of 1 °C × 1 °C for climatic data.

2.2.4 Suitable planting boundaries of winter wheat

The limitations of the suitable planting boundaries of winter wheat used in this research was provided by Jiang (2008). He found that the average temperature of growth period should be between 4 ~ 18 °C. Besides, similar to possible planting boundary, the suitable planting environment is also limited by the humidity condition. That is, for non-irrigated regions precipitation during growth period of winter wheat should exceed

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100 mm (China Crop Climatic Division Cooperation Group, 1987).

$$S_i = \begin{cases} 1, \text{growthavetair} \geq 4\,^{\circ}\text{C}\,\&\,\text{growthavetair} \leq 18\,^{\circ}\text{C}\,\&\,\text{growthpr} \geq 100\,\text{mm} \\ 0, \text{growthavetair} < 4\,^{\circ}\text{C} \| \text{growthavetair} > 18\,^{\circ}\text{C} \| \text{growthpr} < 100\,\text{mm} \end{cases} \tag{3}$$

As for the value of grids in Eq. (3), they are assigned with 1, otherwise assigned with 0, with i denoting the number of grids within the possible planting boundary of China.

Because there might be positive impacts of climate change on the winter wheat growth period, we have taken temperature and precipitation within the growth period into consideration to depict the suitable planting regions in China.

2.2.5 Classification of winter wheat varieties

China Crop Climatic Division Cooperation Group (1987) found that there exist 4 south boundaries for winter wheat varieties in China, namely springness, weak winterness, winterness and strong winterness. Of the 4 boundaries, wheat varieties along the winterness boundary can not get through the vernalization period in South China owing to delay or failure in earing, whereas some springness varieties can not be planted in other zones because of the cold winter in the north. The fact that different winter wheat varieties have different characteristics calls for the necessity of winter wheat classification. Therefore, we use Zhao (2010) description of winter wheat growth period and number of days to classify the winter wheat in China based on the number of days of the growing period (Table 1).

3 Results and discussion

3.1 Impacts of climate change on sowing and harvest date of winter wheat in China

Before presenting our results, we first consider the impact of several important factors on the sowing and harvest date of winter wheat in China, such as annual extreme minimum temperature, as shown in Table 2. We calculate the values of the impact factors for each meteorological station by statistication of daily temperature, daily minimum temperature and daily precipitation simulation results of the MME, using bilinear interpolation. We then construct a multiple stepwise regression model for the impact factors and the station observations of sowing and harvest date. The regression model for the sowing date can be as expressed as: $Y = 312.994 - 6.3528X_1 + 8.28901X_3 - 0.0131637X_7 + 0.183057X_{10}$, ($R^2 = 0.74259$, RMSE = 8.32). The results show that the effect of X_1, X_3, X_7 and X_{10} is positive on the sowing date. Furthermore, the regression model for the harvest date can be expressed as: $Y = 136.621 - 3.68534X_3 + 0.269486X_8$, ($R^2 = 0.695211$, RMSE = 13.35). As shown in Table 3, the variables X_3 and X_8 had positive impacts on the harvest date. Finally, we calculate the winter wheat sowing and harvest date in China for the base period, 2040s and 2070s, using the MME simulations as the climatic background. With regard to the spatial distribution, the sowing and harvest date shows a delayed trend from south to north where the sowing date is earlier in north than in south, as illustrated by Fig. 1. Moreover, we find that the sowing date ranges between 231 ~ 308, 239 ~ 307, and 243 ~ 312, while the harvest date ranges between 63 ~ 238, 60 ~ 231 and 59 ~ 229 for the base period, 2040s and 2070s, respectively.

As shown in Figs. 2 and 3, the impacts of climate change on winter wheat sowing and harvest date in China are significant. In 2040s, the sowing date in the Huang-Huai-Hai region and in the northwestern part of China will be delayed, among which the Tibetan Plateau has the largest delay in terms of days. In most part of southeastern

China the sowing date will shift to an early date, and the number of days will increase and move from northwest to southeast. Compared with 2040s, the regions that show a delayed sowing date will expand southward and the number of delayed days will increase in 2070s. Concerning harvest date, it will be delayed in central China along the line Shandong–Henan–Shaanxi–Sichuan and Yunnan provinces whereas in other regions it will increase. Similar to 2040s, the harvest date shows a delayed trend in central China, but with a decreasing number of delayed days in 2070s. While the area that shows a delayed harvest date is shrinking, in other regions of China the harvest date will shift to an earlier date and the number of days will increase compared to 2040s. To conclude, in the future the sowing date will shift to an earlier date and the harvest date will shift even earlier. In some areas, the sowing date will be delayed while the harvest date will shift to an earlier date. Thus, the growth period of winter wheat will be shortened due to climate change.

3.2 Impacts of climate change on possible planting boundaries of winter wheat in China

Figure 4 shows the possible planting boundaries of winter wheat in China. The red lines denote/indicate the boundary of the base period, one of which spread along southwestern Liaoning – Beijing – north central Hebei – central Shanxi – central Shaanxi – north Ningxia – southeastern Gansu – southwestern Inner Mongolia – southeastern Sichuan and south Tibet. In addition, one circle is in south central Xinjiang and the third one is marked out in northern Xinjiang. That implies that the possible planting region of winter wheat is in the south of the first red line and in part of Xinjiang. To verify the reliability of this boundary, we compare our results with previous studies. Wang et al. (2012) analyzed the spatial variation of possible planting region of winter wheat during 1961–2010, using climatic observations obtained from 553 meteorological stations. Although the climatic data source and the simulation of the GCMs in our study are different, the boundary we found is similar to that of Wang et al. (2012), which indicate that our results are reliable.

Moreover, the green and blue lines denote the possible planting boundaries of winter wheat in China under RCP4.5 scenario for 2040s and 2070s respectively. As illustrated by Fig. 4, the north possible planting boundary moves northward and extends westward, while the south possible planting boundary rises and spreads in south Hainan and Taiwan. In 2040s, the planting boundaries of winter wheat will shift from southwestern to central Liaoning province, move northward to Hebei and Shanxi province and cover whole of Shaanxi province. It will extend to the northwestern Inner Mongolia Autonomous Region and move to the east of Gansu province. From there it moves westward to Sichuan province, stretch northwestward to the Tibet Autonomous Region and extends northwestward to the Xinjiang Autonomous Region, making it the province with the largest increase in area of possible planting region in China. Compared to 2040s, the north boundary line in 2070s is in Liaoning, Hebei, Shanxi, Inner Mongolia, north Xinjiang and moves further northward, making Inner Mongolia a potential main producing area of winter wheat in China. The west boundary line in 2070s is in Gansu, Sichuan, Tibet and extends further northwestward. Here, the boundary in Xinjiang Autonomous Region extends northwestward and expands south simultaneously, resulting in the province with the largest increase in area of possible planting region in China.

3.3 Impacts of climate change on suitable planting regions of winter wheat in China

Figure 5 presents the suitable planting regions of winter wheat in China, of which the red lines denote the boundaries for the base period. Our simulation shows that the north boundary spreads along the line south Liaoning – south Beijing – south Tianjin – south Hebei – south Shanxi – south Shaanxi – east Sichuan – north Yunnan and south Tibet. The south boundary spreads along Guangxi Autonomous Region and south Guangdong province. Besides the regions between the north and the south boundaries, the south central Xinjiang Autonomous Region also belongs to the suitable planting region. To verify the reliability of the suitable planting boundary, we compare the results with Zhao's (2010) study. By contrast, in Zhao's study, the winter wheat planting zones are divided by considering geographical environment, natural conditions, climatic factors, cropping system varieties, production level, cultivation characteristics, diseases and insect pests (Zhao, 2010). Yet the suitable regions simulated in our study are located within Zhao's (2010) planting zones, implying that the results are consistent with previous studies and therefore reasonable.

Furthermore, the green line and blue line denote the suitable planting boundaries of winter wheat in China under RCP4.5 scenario for 2040s and 2070s respectively. As shown in Fig. 5, the north suitable planting boundary moves northward and expands westward, while the south suitable planting boundary shifts towards north. At the same time, the part located in Xinjiang Autonomous Region also expands. Under RCP4.5 scenario, the north boundary moves northwestward in 2040s, shifts to south central Liaoning province and expands to north Beijing and Hebei province. It further moves to central Shanxi province, shifts to north of Shaanxi province and moves westward in south Sichuan province. While the changes are negligible in Yunnan province, the north boundary moves a bit northward in southern Tibet Autonomous Region. With regard to the south boundary, it expands to southern Fujian province, moves northward in Guangdong province while it increases to a large area in Inner Mongolia and expands northwestward in Xinjiang. Compared with 2040s, the suitable planting boundaries of winter wheat moves northwestward in Shanxi and Shaanxi provinces, whereas in Inner Mongolia it extends northeastward in 2070s. Moreover, the changes of the north boundary in other provinces are negligible except for Xinjiang Autonomous Region. Such is extent of the expansion in Xinjiang that it is the province with the largest increase in area of possible planting region in China. Moreover, the results about the south boundary for winter wheat in this study show a northward expansion. Here, Xinjiang and Inner Mongolia have the largest increase of suitable planting area in China, and therefore the most sensitive regions to the impacts of climate change.

3.4 Impacts of climate change on winter wheat planting of different varieties in China

There is a significant distinction between winterness winter wheat and springness winter wheat eco-climatic region. Four eco-climatic regions can be delineated in China based on the duration of the growth period: strong winterness (growth period > 250 d), winterness (growth period 220–250 d); springness (growth period 175–220 d), and strong springness (growth period < 175 d). Accordingly, these four eco-climatic regions are distributed from north to south, as shown in Fig. 6.

In this context, Li et al. (2013) estimated the distribution of planting zones for different winter wheat varieties based on climatic observations obtained from 680 meteorological stations during 1951–2010. Their study made seven findings. First, the north boundary of strong winterness winter wheat spread along the line south Liaoning – north Hebei – north Shanxi – north Shaanxi – south Gansu – central Sichuan and south Tibet. Second, the south boundary of strong winterness winter wheat spread along the line central Jiangsu – south Henan – south Shaanxi – south Gansu – central Sichuan and south Tibet. Third, the north boundary of winterness winter wheat spread along the line south Beijing – central Hebei – north Henan – north Shaanxi – south Gansu – west Sichuan and south Tibet. Fourth, the south boundary of winterness winter wheat spread along the line Shanghai – south Anhui – north Hubei – south Shaanxi and east Sichuan. Fifth, the north boundary of weak winterness winter wheat spread along the line south Shandong – north Henan – central Shaanxi – central Sichuan and south Tibet. Six, with regard to the south boundary of weak winterness winter wheat, Li et al. (2013) found that it spread along the line south Zhejiang – central Jiangxi – central Hunan – south Guizhou and north Yunnan province. Seven, the north boundary of springness winter wheat spread along the line north Jiangsu – north Henan – south Shaanxi – central Sichuan and north Yunnan but there is no south boundary of springness winter wheat in China. In our study, most of the eco-climatic regions specified for each of the four winter wheat varieties are located within the boundaries lined by

Li et al. (2013). That implies that the eco-climatic region division used in this study is reliable.

Our estimates for 2040s indicate that there is little variation of north boundary for springness winter wheat and the north boundary of weak winterness winter wheat moves northward in Jiangsu, Anhui and Henan provinces. We also find that the north boundary of winterness winter wheat varies slightly in Hebei and Gansu provinces, while the north boundary of strong winterness winter wheat shifts along the north possible planting boundary. Compared with 2040s, we find that the division of eco-climatic regions specified for each winter wheat varieties shift significantly in 2070s. As such, the north boundary of springness winter wheat shifts northward significantly and is mainly distributed in south Zhejiang, north Jiangxi, central Hunan, north Guizhou and north Yunnan provinces. Moreover, the north boundary of weak winterness variety moves not only to south Shandong and north Henan provinces, but also westward to Sichuan province. In addition, the north boundary of winterness variety show little shift except new appearance in south central Xinjiang Autonomous Region. Finally, our results show that the north boundary of strong winterness variety shifts along the north possible planting boundary.

4 Conclusions and implications

As a reflection of the growing concerns about the impacts of climate change on economic sectors around the globe, there is an increasing number of studies on the impacts of climate change on agriculture in China. However, there are very few empirical studies that use rigorous methodologies and high quality data to take China's climate policy one step forward by moving from ex-post analysis to forecasting. In this study, we construct a multiple stepwise regression model for winter wheat sowing and harvest date, combined with influencing factors, to simulate the spatial distribution of winter wheat growth period within China. Using an empirical model based on agricultural meteorological observations and the IPCC AR5 GCMs simultations, we make four analytical contributions. First, the results of the present study indicate that the sowing date shows a delayed trend from north to south where the sowing date is earlier in the north than in the south. We also find that the harvest date shows a delayed trend from south to north. As a result, the growth period of winter wheat will be shortened in China due to the impacts of climate change. Second, under RCP4.5 scenario for 2040s and 2070s, the north possible planting boundaries of winter wheat in China moves northward and expands westward in the future, while the south possible planting boundary rises and spreads in south Hainan and Taiwan. The simulated boundaries expands largely in Xinjiang Autonomous Region and moves northeastward in Inner Mongolia Autonomous Region, implying that Xinjiang and Inner Mongolia are the provinces with the largest increase in area of possible planting regions in China. Third, while the north suitable planting boundaries of winter wheat in China moves northward and expands westward in the future, the south boundaries moves northward and the boundaries in Xinjiang ends to expand. Fourth, with regard to the four eco-climatic regions of winter wheat planting, we find that the north boundary of springness winter wheat moves northward and the north boundary of weak winterness variety shifts northward in the east and moves westward in the west under RCP4.5 scenario. The north boundary of winterness variety show no apparent shift, but the appearance of suitable eco-climatic region for winterness variety in south central Xinjiang in 2070s is notable. Finally, the north boundary of strong winterness winter wheat shifts along the north possible planting boundary. The implications of our findings are significant: China can take advantage of the shortened growth period by improving the multiple crop index. Furthermore, it is imperative to adjust the planting dates according to the conditions posed by climate change to reduce the impacts on winter wheat from cold damages and other disasters, especially around the possible planting north boundary which will move northward. In this context, Xinjiang and Inner Mongolia are the most sensitive regions to the impacts of climate change on winter wheat planting in China, and therefore priority should be given to design adaptation strategies for these provinces. As the north boundaries of winter wheat varieties moves northward, we should also adjust the layout of different varieties according to the changes of suitable planting regions to reduce the risks of climate change.

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Table 1. Classification standards of different varieties boundaries of winter wheat.

Variety	strong winterness	winterness	weak winterness	springness
Growth period (d)	> 250	$220 \sim 250$	$175 \sim 220$	< 175

Table 2. Impact factors of planting and harvest date of winter wheat in China.

possible factors	variable description	sowing date	harvest date
X_1	annual extreme minimum temperature	√	
X_2	average minimum temperature of the coldest month		
X_3	average temperature of the coldest month	√	√
X_4	annual average temperature		
X_5	annual accumulated temperature above 0 °C		
X_6	annual precipitation		
X_7	annual solar radiation	√	
X_8	number of days with temperature $0 \sim 3$ °C		√
X_9	number of days with temperature $0 \sim 7$ °C		
X_{10}	number of days with temperature $0 \sim 12$ °C	√	

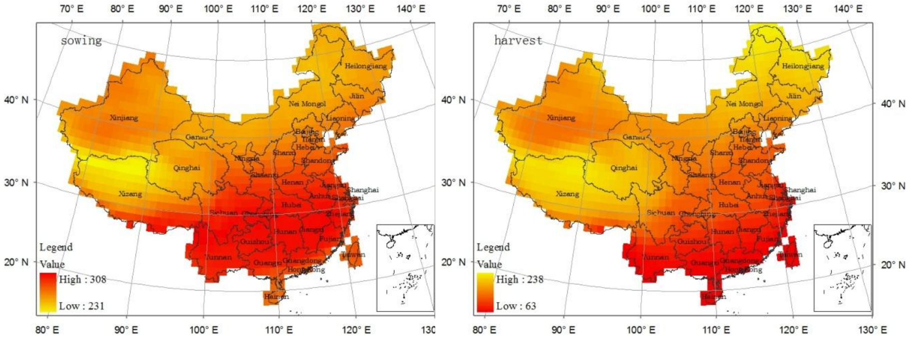

Figure 1. Distribution of sowing and harvest date of winter wheat in China in baseline.

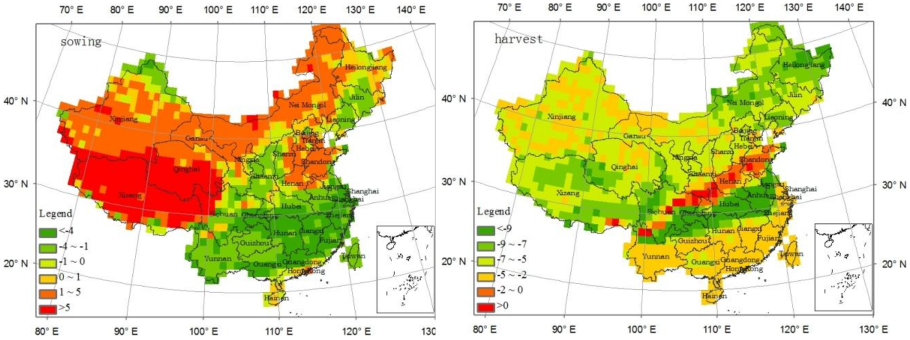

Figure 2. Distribution of sowing and harvest date changes of winter wheat in China in 2040s.

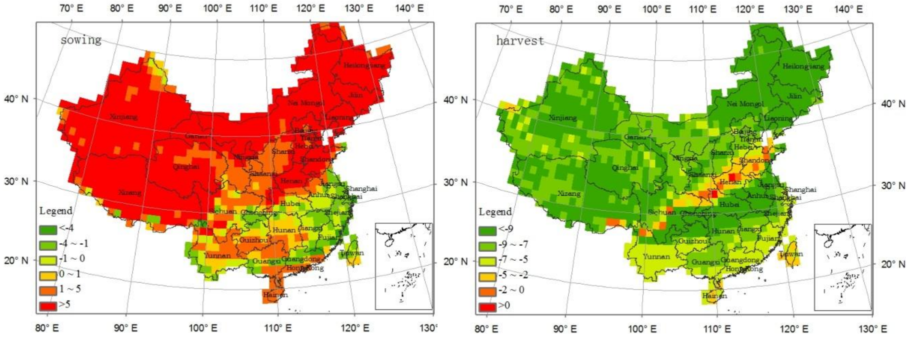

Figure 3. Distribution of sowing and harvest date changes of winter wheat in China in 2070s.

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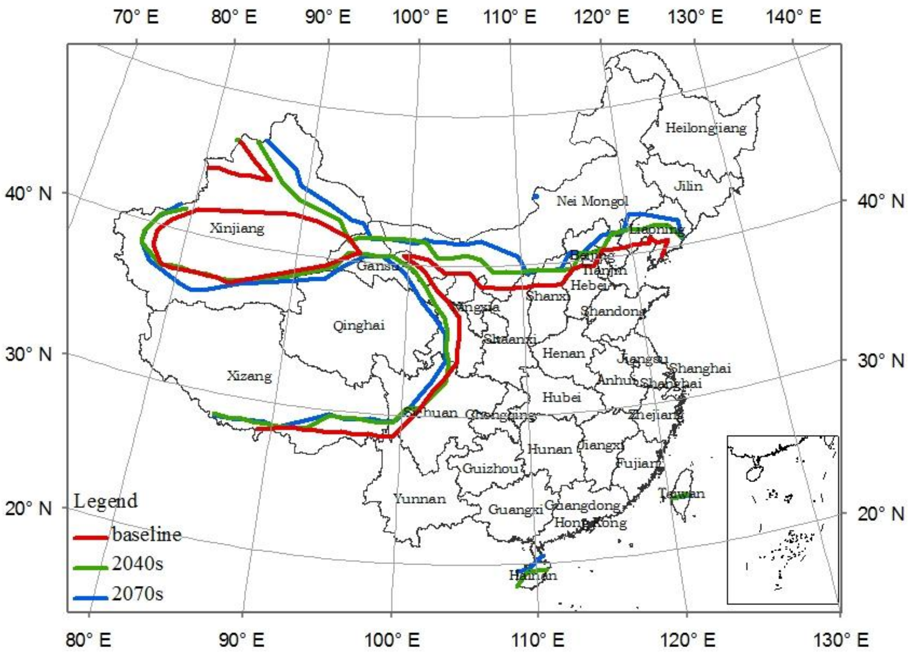

Figure 4. Possible planting boundary of winter wheat in China.

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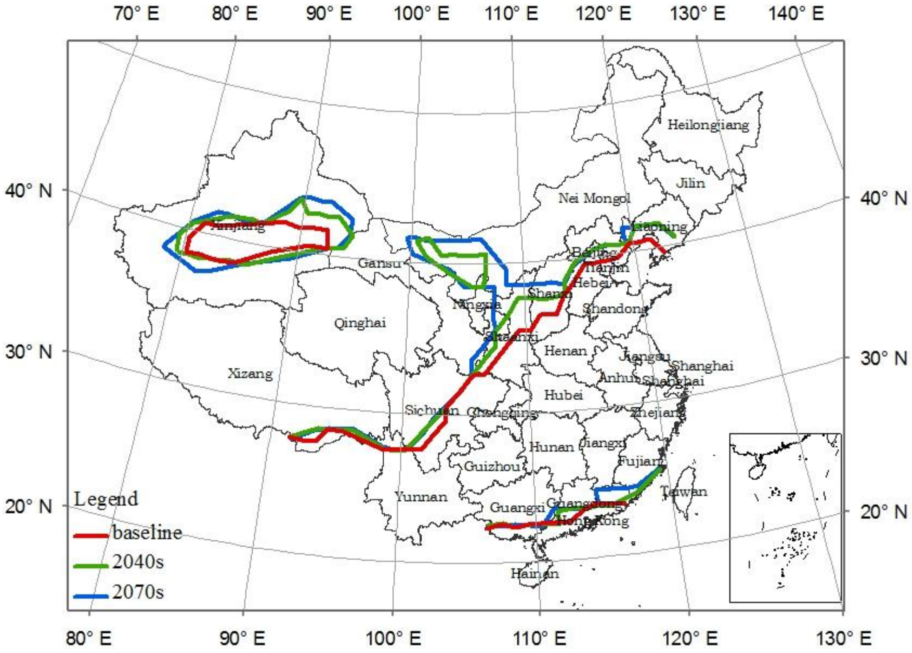

Figure 5. Distribution of suitable planting regions of winter wheat in China.

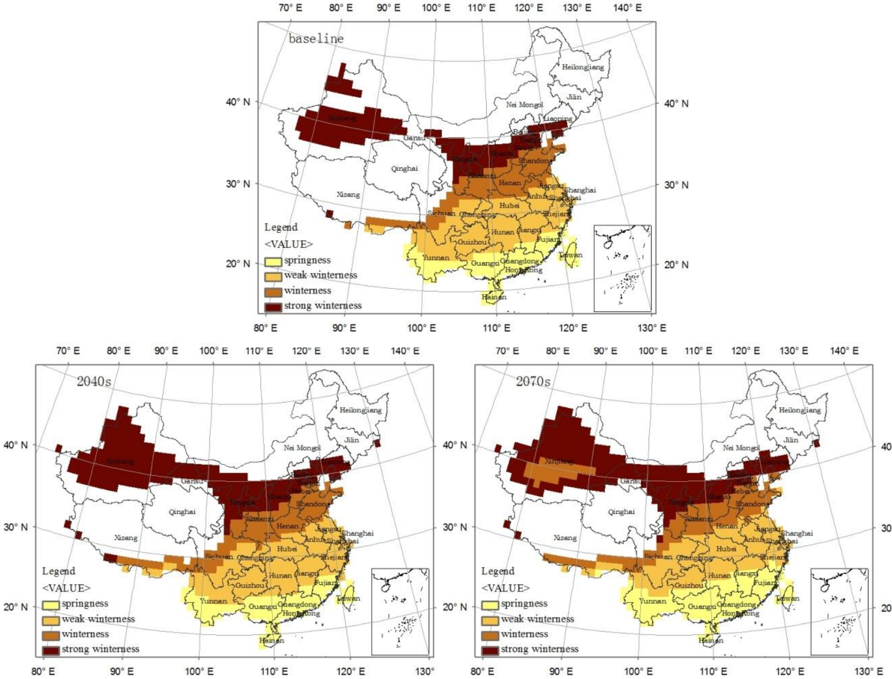

Figure 6. The geographical shift of planting boundary of winter wheat varieties in China.

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