Impacts of global warming on the cropping systems of China under technical improvements from 1961 to 2016

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Core Ideas

- The cumulative temperature demand has increased for multiple cropping systems.
- China's crop planting areas for double-cropping systems were compressed.
- High grain production potential occurred in the transition area.

Abbreviation

AAT0, annual accumulated temperature above 0℃;

DCS, double-cropping system;

MCS, multiple cropping system;

SCS, single-cropping system;

TCS, triple-cropping system

Abstract

The multiple cropping systems (MCS) have been crucial for China's food security due to its limited arable land and the increased population for hundreds of years. Global warming has significantly affected MCS in China during recent decades. However, whether global warming has influenced the MCS in China under technical improvement is still uncertain and has received great attention. Thus, the current study aims to evaluate the impacts of global warming within the improvements of crop cultivars on MCS in China and analyze the changes in cropland and actual cropping area during past 5 decades. Our results showed that the cumulative temperature above 0°C for the double-cropping system (DCS) and triple-cropping system (TCS) respectively increased by 400°C and 100°C compared to the values in the 1980s. The northern limit of the DCS shifted southward, while the northern limit of the TCS moved northward. The cropland of the single-cropping system and triple-cropping system increased while the cropland of the DCS decreased. Specifically, the winter wheat area, which represents the DCS in northern China, decreased during the past decades. Similarly, the double–rice cropping system area, which represents the TCS in southern China, decreased as it was partly replaced by single-rice cropping system. Our study indicated that the cropping intensity in China decreased during past decades, and the full use of MCS will lead to high grain production potential in the transition area. The results will be beneficial for optimizing the cropping distribution across China and enhance the food security.

Keywords: climate change; multiple cropping system; cumulative temperature; cropland; crop intensity

1 Introduction

Food security has always been a key issue in the international society (Fouilleux et al., 2017; He et al., 2019). The world population has doubled while the cropland area has increased by only 12%, which intensified the challenges of food security (FAO, 2012). As the country with the largest population in the world, food security in China is always an extremely crucial issue, which is important not only for social stability but also for global food patterns (Wang et al., 2015). However, the unprecedented growth of both the economy and the population has led to a decrease in the cropland area since the 1980s across China (He et al., 2013). The growing competition for land, water, energy and the overexploitation of fisheries has seriously impaired the production of food (Verburg et al., 2013; Wu et al., 2014). Thus, how to use limited arable land to feed an increasing population has received great attention.

Generally, improving cropland use intensity is an effective way to increase grain production. Multiple cropping systems (MCS) have been existed in China for a long history, and these systems effectively increased the cropping index. Our previous study showed that the multiple cropping indices in China were among the highest levels in the world, which greatly contributed to China’s food security (Yang et al., 2015). For example, the grain production capacity in China has massively improved, and the grain output has continuously increased for more than 15 years since 2004 (Lu et al., 2019). Generally, China's MCS includes three types: single-cropping system (SCS), double-cropping system (DCS) and triple-cropping system (TCS) (Yang et al., 2015). The SCS is the main cropping system in high-latitude areas in northern and southwestern China, which have relatively low temperature conditions. For instance, Northeast China is a typical SCS region. Single-rice, spring maize, spring soybean and spring wheat are the main crops in this area (Yin et al., 2016a, 2016b; Liu et al., 2018b). The DCS is mostly distributed in middle China, especially in the North China Plain, which provides 61% of winter wheat in China (Sun et al., 2011). Winter wheat-summer maize and winter wheat-single rice cropping systems have been the dominant DCS types. The TCS is mainly concentrated in southern China with abundant hydrothermal conditions, especially in the middle-lower Yangtze River Plain. Double rice and winter wheat or winter rape rotation are the dominant cropping systems in this area (Liu et al., 2015).

Global warming has significantly influenced China's agriculture during the last five decades (e.g. Yin et al., 2016d). The distribution of potential MCS is mainly influenced by global warming and agronomic technological progress. The current MCS boundary in China was defined using the indexes established in the 1980s, which mainly includes climate parameters while ignores the crop cultivars (Liu and Han, 1987). Mapping the current boundary of multiple cropping systems in China under the impacts of global warming and crop variety improvements is essential for new national agricultural structural adjustments. Generally, the local potential multiple cropping index could theoretically increase due to the increase in accumulated temperature (Tao et al., 2006). For example, global warming is beneficial for winter wheat, which can safely overwinter in the northern boundary of the North China Plain (Sun et al., 2015). Global warming would shorten the crop growth period and reduce the yield without management adaptations (Lobell et al., 2011; Olesen et al., 2000, 2011; Yin et al., 2016c). Changing sowing dates and adopting longer growing season cultivars have been identified as efficient adaptation strategies to cope with climate change (e.g., Bassu et al., 2009; Olesen and Bindi, 2002). Obviously, currently used crop varieties with longer growing seasons require higher accumulated temperature than before, which could affect the spatial variation in MCS in China (i.e. Liu et al., 2013). Previous studies have indicated that the growing season of wheat, maize and rice in China has extended in recent decades (e.g., Tao et al., 2006, 2013; Xiao et al., 2013). In this case, the classification indices of MCS could change with the updates of crop cultivars and changes of sowing dates. Generally, current crop spatial distribution was evaluated by remote-sensing or national statistical data, which has been widely used to represent the actual farmer's adaptation to climate change or land use policy (Yang et al., 2015). However, relatively little work has been done to update the MCS indices considering the current crop varieties and technological improvements in China.

Impacts of climate change on cropping systems have been conducted for a long time, while most studies focused on crop plant physiology, crop yield, crop modeling and climate scenarios, limited reports have payed attention to cropping north limits (Keating et al., 2003; Yang et al., 2015; Zhao et al., 2018). Previous studies showed that the northern limits of cropping systems in China have moved northward and westward, both the potential winter wheat and paddy rice planting areas in China have expanded due to global warming (Yang et al., 2011; 2015). The production center of major grain crops (wheat, maize and rice) has transferred northward to varying degrees (Liu et al., 2015, 2018b; Sun et al., 2019). However, these studies only considered the potential impacts of global warming while ignored the contributions of crop cultivars and technical improvements. On the other hand, farmers played very important roles in adapting agriculture to climate change based on their own understanding of the climate environment, soil conditions, water conditions and market demands. Farmer activities have experienced dramatic changes in multiple cropping systems and productivity (Li et al., 2015). Various studies have investigated the response of crop phenology, yield and production to climate change (e.g., Li et al., 2014; Liu et al., 2015). However, few studies have investigated how local farmers adapted to climate change by analyzing real situations in crop production, which is significant for estimating potential productivity.

The main objectives of this research were to (i) update the classification index of MCS in China based on the updates of crop varieties, (ii) quantity the changes of northern limits and crop planting areas of MCS under global warming and technical improvements during the past three decades, and (iii) investigate if the real crop production matched the movement of the boundary of MCS under global warming over the past three decades.

2 Materials and methods

2.1 Study area

The study area included the entire mainland area of the People's Republic of China, which comprises almost 1.4 million km^2 of arable area (Fig. 1). Specifically, cropping intensity decreased from the southeast to the northwest of China because of the uneven distribution of temperature and rainfall. Generally, China's MCS comprises three types: single-cropping system (SCS), double-cropping system (DCS) and triple cropping system (TCS). The SCS is mainly concentrated in northern and southwestern China, which have relatively high latitude and low temperature conditions. The TCS usually distributed in the south of China, which have abundant hydrothermal conditions.

2.2 Data resources

Three types of datasets were included in the study, including the daily climate datasets, national historical crop production data and national remote sensing data. The daily meteorological data, including maximum and minimum temperatures, average relative humidity, bright sunshine hours and average precipitation, of 839 weather station sites from 1961 to 2016 were obtained from the National Meteorological Information Center of the China Meteorological Administration (CMA). The crop phenological data, comprising crop phenology, aboveground dry matter, yields and management practices, from 2010 to 2012 were also obtained from the CMA (Fig. 1). Generally, 100 phenological observation sites from the DCS and TCS were adopted to analyze the cumulate temperature for identifying different cropping systems.

The statistical data for the annual crop sown area (wheat, single-rice and late-rice) at the county level from 1985 to 2015 were obtained from the shared database of the National Bureau of Statistics. The data of cropland distribution and actual multiple cropping area estimated by remote sensing in 2015 were obtained from the Resource and Environment Data Cloud Platform of the Institute of Geographic Sciences and National Resources Research.

2.3 Changes of the northern limits of multiple cropping systems

Generally, temperature was always the key environmental factor that influences the crop growth and decides how many crops can be grown in each region, which has been widely used to judge the MCS in China (Yang et al., 2015). According to the standard farming system in China, the accumulated temperature in the winter wheat-summer maize growing season was defined as the double-cropping system (DCS) limitation, and the accumulated temperature in the early-rice, late-rice and rape growth periods was defined as the triple-cropping system (TCS) limitation, which was established in the 1980s (Liu and Han, 1987). Specifically, if the area where the cumulative temperature cannot satisfy the demand of DCS, which will be defined as SCS. The crop phenological data from local agricultural meteorological experimental stations were used to update the MCS index in China based on the previous standardized definition. The minimum accumulated temperature during the crop growing season in different cropping systems was defined as the northern-most line as before. The average cumulative temperature during the crop growing season in different cropping systems was defined as the average line, and the area between the two lines was defined as the transition area in the study.

The cumulate temperature during crop growing period was used to analyze the changes i of MCS indices under technical improvement (mainly the updates of crop cultivars in the study). The observed crop phenology datasets showed that the cumulate temperature during the major crop growing period increased during past decades (Table 1), and the changes of cumulate temperature during crop growing period was used to represent the cultivars shifts. This is mainly because the adaptation of longer growing season cultivars was the major factor that led to the increasing trend of cumulate temperature (Liu et al., 2013). However, due to the limited existed phenological data before 1990, the previous indices generated by Liu and Han (1987) was adopted to represent the crop variety parameter before 1990 in the study.

The annual accumulated temperature above 0℃(AAT0) was used to analyze the limitation lines on the country scale (Table 2). AAT0 was calculated as the summation of the daily average temperature above the baseline temperature (0℃) for the period with a temperature steadily above 0℃(Fischer et al., 2002). The calculation of AAT0 is shown as follows:

$$AAT0 = \sum_{i=a}^{b} T_i\ ,\ \ T_i \geq 0 \qquad (1)$$

where *a* and *b* are the starting and ending dates of the period with temperatures steadily above 0℃, respectively. T_i represents the average air temperature on day *i*. The research period mainly includes two parts, namely the period from 1961 to 1980 and the period of 1981-2016. This is mainly because the traditional limitation of MCS in China was established in 1980s, which had been widely used in China, and can be easily compared in the current study. The AAT0 was ranked from lowest to highest and the 20^{th} percentile of AAT0 value was chosen as the indicator for the thermal conditions during the two periods for each individual station (Yang et al., 2015).

2.4 Meteorological interpolation

Anusplin was used in the study to determine the limitation lines by using the observed temperature datasets in China, and it is a professional interpolation software package developed by the Australian National University based on the thin plate smooth spline technique (Hutchinson and Xu, 2013). Thin plate spline can determine the degree of smoothness of an output surface from the sampling sites through generalized cross validation (Basconcillo et al., 2017). The Anusplin model is particularly suitable for processing time series of meteorological data under a complex mountain environment and performs better than other spatial interpolation methods (e.g., IDW and Kriging) (Liu et al., 2018a; Zhu et al., 2019). Thus, Anusplin version 4.4 was adopted in the study. The spline number was 2, and the longitude, latitude and elevation were covariates. The output horizontal resolution was 1 km. More details on the Anusplin model can be found in the ANU website (http://fennerschool.anu.edu.au/research/products/anusplin-vrsn-44).

2.5 Spatio-temporal change in crop sown area

This Sen's slope estimator was used to estimate the magnitude of trends in time-series data to evaluate the real situation in crop production under climate change over the past three decades (Sen, 1968). It can limit the influence of outliers on the slope through comparison with linear regression. The calculation formula is as follows:

$$b = Median(\frac{x_j - x_z}{j - z}) \quad (2)$$

where x_j and x_z represent the data values at times j and z (j>z), respectively, and b represents the annual increment under the hypothesis of a linear trend.

The winter wheat planting area could represent a double-cropping system according to the national standard farming system (Yang et al., 2015). This mainly because the growth period of winter wheat in China is generally from October of the previous year to early June of the next year, and another season crop can be grown from June to October, such as summer maize and summer soybean. On the other hand, the double-rice cropping area could represent a triple-cropping system mainly because the growing period of double-rice in southern China is generally from April to October, and the overwintering crop can be grown in the winter, such as winter-rape, winter-wheat or vegetables. Similarly, the late-rice sown area was used to represent the double-rice cropping area (Liu and Han, 1987). In addition, the national census data at the county level were used to analyze the spatiotemporal change in the sown area of winter wheat, single-rice and late-rice from 1985 to 2015.

3 Results

3.1 Changes of the indices for multiple cropping systems in China

Our results showed that the AAT0 significantly increased at a rate of 0~300℃ per decade in most parts of China during the period of 1961-2016. The mean AAT0 increased by an average of 66.3℃ per decade (Fig. 2). The AAT0 showed a decreasing trend mainly in the mountain areas, which accounted for less than 3% of the total climate sites. The annual cumulative temperature for the DCS increased almost 400℃ during the period of 1981-2016 compared to the period of 1961-1980 (Fig. 3). It ranged from 4400℃ to 5300℃, and the average level reached 4700℃. The annual cumulative temperature of the TCS increased approximately 100℃ in the period of 1981-2016 compared to the period of 1961-1980 (Fig.

3). It ranged from 6000°C to 6700°C, and the average level was 6200°C. Furthermore, the new indices were used in the study to map the new MCS in China (Table 2).

3.2 Changes of the northern limit and cropland for multiple cropping systems in China

Our results showed that the northern limits of the DCS have generally moved southward during the last three decades, especially in Hebei, Shanxi and Sichuan provinces (Fig. 4). The northern limits moved approximately 30 km, 20 km, 30 km and 50 km southward in the provinces of Hebei, Shanxi, Gansu and Sichuan, respectively. Different variation tendencies occurred in the TCS. Our results showed that the northern limit of the TCS moved northward during the past three decades, especially in Anhui, Zhejiang and Hubei provinces (Fig. 4). The northern limits moved approximately 90 km, 50 km, 60 km and 30 km northward in the provinces of Zhejiang, Anhui, Hubei and Yunnan, respectively, compared to the period of 1960-1980.

The results also showed that the transition area between the SCS and DCS was mainly distributed in the mountain area from Northeast to Southwest China (Fig. 5). The transition area had a total of 37,500 km^2 of cropland, which was mainly concentrated in northern Hebei Province and Jiaodong Peninsula in Shandong Province. This area could be a potential grain production area with enough heat resources in the local climate. The transition area between the DCS and TCS was mainly located in Hunan, Hubei, Anhui and Zhejiang provinces, which covered almost 64,000 km^2 of cropland (Fig. 5). This distribution indicates there could be a large potential yield if the triple-cropping system was adopted in the whole area.

In the period of 1961-1980, the SCS, DCS, and TCS crop planting areas accounted for 39.2%, 44.2% and 16.6% of China's total cropland, respectively. The percentage of cropland in the SCS and TCS region increased by 0.8% and 2%, respectively, while the cropland in the DCS region decreased by 2.8% in the period of 1981-2016 compared to that in 1960-1980 (Fig. 6). The enlarged SCS areas were mainly located in Hebei, Shanxi and Sichuan provinces, with equivalent cropland areas of approximately 2300 km^2, 430 km^2 and 5600 km^2, respectively. Enlarged TCS areas were mainly concentrated in Hubei, Anhui and Zhejiang provinces, with equivalent cropland areas of approximately 17,400 km^2, 3800 km^2 and 8100 km^2, respectively. The double-cropping system was compressed under the impact of climate change and technological development in theory.

3.3 Actual situation of crop production under global warming and variety replacements

Our results showed that the actual crop production situation matched well with the limit lines of DCS and TCS. The actual planting areas of multiple cropping systems estimated by remote sensing in 2015 were mostly below the northern limit line of the DCS (Fig. 7a). Interestingly, the actual late-rice planting area in 2015 was mainly concentrated in the south of the limit line for the DCS, except for a few counties in Anhui Province (Fig. 7b). The results also showed that the winter wheat sown areas decreased gradually over the past three decades, especially in Gansu Province (Fig. 8a). This result indicated that the local double-cropping system was gradually transitioning to a single-cropping system to a certain extent. Interestingly, we found that the late-rice planting area decreased around the northern limit line of the TCS (Fig. 8b), while single-rice increased during the past three decades (Fig. 8c). This result means that the local triple-cropping system was gradually transitioning to double-cropping. Although the northern limit had moved northward in theory, local farmers did not adapt to the climate change impact.

4 Discussion

4.1 Updating the MCS indexes

Technologies have played important roles in coping with climate change in China's agricultural production (e.g. Yin et al., 2016b, 2016d). Generally, changes in MCS were not only affected by climate change but also by other factors, such as variety replacements, agricultural management and policy guidance (Deressa et al., 2009). Obviously, global warming has extended the length of the potential growing season, allowing earlier planting, maturation and harvesting, especially in the cool and warm regions (e.g. Yin et al., 2016a, 2016c, 2016d; Tao et al., 2006, 2013). Moreover, less severe winters allow more productive cultivars of winter crops to be grown (Olesen et al., 2011). As the development of plant breeding, more and more crop varieties with longer growth period have been widely used to adapt to global warming, which may change the demand of cumulative temperature during crop growing period (Tao et al., 2013; Sun et al., 2015). Our results showed that both the annual cumulative temperature for the DCS and TCS increased compared with the indices used in 1980s by using current used crop varieties. Actually, global warming has positive effect because of the increase in daily average temperature during crop growth period. On the other side, crop variety replacement and agricultural management development accelerated this increasing tendency. Crops with longer growing period can make full use of temperature resources and efficient agricultural management can save the time between different crop seasons (Liu et al., 2013). Updated indices of MCS using new crop varieties could be more suitable for evaluating the spatial distribution of multiple cropping system in China.

4.2 Changes of the northern limitation line of MCS in China

Our results showed that the limited line of the DCS in China moved southward and that the limitation line of the TCS moved northward slightly during the study period, which was a bit different from a previous research (Yang et al., 2015). This is mainly because new indices considered crop variety replacements. Moreover, the Anusplin meteorological interpolation method applied in the study considered the effects of the terrain factor, which also led to differences from previous research that used IDW or Kriging interpolation methods (Yang et al., 2015; Basconcillo et al., 2017). Although the cumulative temperature during the crop growing period in the DCS region increased by almost 400°C, the northern limit line of the DCS did not change dramatically. This is mainly because the northern limit line of the DCS mostly occurred at the edge of the mountain and plain areas in China. The elevation difference could slow the changes of the northern limit lines. In contrast, despite the cumulative temperature during the crop growth period in the TCS increased only 100°C, the northern limit line of the TCS changed dramatically due to the flat terrain. Our results were well supported by the actual production conditions of the cropping system in China (Fig. 7) and could be beneficial for future agricultural structure adjustments.

4.3 Changes of the practical MCS boundary

Previous research indicated that cropping areas of all cereals may expand northwards under global warming (Olesen and Bindi, 2002). Both the potential winter wheat and paddy rice planting areas in China have expanded northwards under global warming (Yang et al., 2011). Although global warming has enlarged the theoretical area of the DCS and TCS, the increasing temperature demand during the growth periods of the new crop varieties would offset the variation tendency. Actually, local farmers' adaptations led to dramatic changes in multiple cropping systems (Li et al., 2015). For example, farmers adopted double-cropping systems instead of triple-cropping systems in the middle-lower Yangtze River Plain in order to save agricultural inputs (Tong et al., 2003). Our results also indicated that the winter wheat planting area in the transition area of the SCS and DCS decreased over the past three decades. The increased cumulative temperature demand of winter wheat growing season is one factor (Xiao et al., 2013). The national rotation and fallow policy in the North China Plain might be another factor leading to the reduction of winter wheat planting area (Jiang et al., 2020a, 2020b). On the other hand, the northern limit of the TCS moved northward during the study period, while the double-cropping rice sown area was gradually replaced by single-cropping rice. There is a growing tendency for people who live in rural areas and work in the city to earn a higher income, which causes severe labor shortages in the TCS region (Tong et al., 2003). Single-cropping rice with a longer growing season can save labor and achieve a relatively high yield, which has been widely adopted by local farmers. On the other hand, the local promotion of direct-seeding rice with low-input demand in recent years could cause the southward shift of double-cropping rice because direct-seeding rice increases the accumulated temperature of the growth period in the field compared to that of the transplanting rice (Tong et al., 2003). It should be noted that the transition area between the

DCS and TCS would have a relatively high potential grain yield if the triple-cropping system was widely adopted.

4.4 Perspectives and implications

China always meet with high food security demand due to the large amount of population and limited crop land, previous studies showed that increasing cropping intensity is an effective way to guarantee food security (Deng et al., 2009; Liu et al., 2014; Qiu et al., 2017). However, whether changes in cropping systems can take place is still uncertain due to the combinations of various factors, such as economic factors, environmental benefits and farmer acceptance (Plourde et al., 2013; Robinson et al., 2015; Wang et al., 2016). Previous studies indicated that climate-smart management can further improve crop yield in China based on agricultural models (Gao et al., 2019; Sun et al., 2018; Wang et al., 2018), and global warming will beneficial for crop production in China. However, our results indicated that the cropping intensity in China has decreased over the past three decades, and we did not make full use of the advantage of global warming in agricultural production. We have a relatively high grain production potential if we make full use of the transition area. For example, we could recover the double-cropping system in Jiaodong Peninsula in Shandong Province and encourage farmers to adopt double-cropping rice in Hubei, Anhui and Zhejiang provinces. However, it is a complex project to balance the land use, economic efficiency and environment protection. To increase the cropping intensity in the transition area, we should firstly try to increase the local economic efficiency and encourage farmers to accept multiple cropping systems. On the other hand, extreme weather events, such as heat stress and drought, were projected to occur more frequently under climate change in the future (Jiang et al., 2019). Further adaptations to cope with climate extremes are extremely important to the sustainable development of multiple cropping systems in China. Meanwhile, breeding high-yield and heat-tolerance varieties is important to increase crop productivity, and climate-smart management is still needed to further improve crop yields in China.

5 Conclusion

Our results showed that the new MCS index is more suitable for identifying the northern limits of MCS. It showed that the cumulative temperature above 0°C for the DCS and TCS increased by 400°C and 100°C, respectively, during the period of 1981-2016 compared to the period of 1960-1980. The northern limitation of the DCS shifted southward, while the northern limitation of the TCS moved northward. Additionally, the cropland of the SCS and TCS expanded accordingly, and the cropping intensity decreased in China during the study period. Specifically, the actual cropping area of either winter wheat or late-rice respectively decreased over the past three decades, while the single-rice planting area increased. Our study indicated that increasing crop intensity and making full use of the transition area are practical strategies to ensure China's food security under global warming.

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References

Basconcillo, J., Duran, G., Francisco, A., Abastillas, R., Hilario, F., Juanillo, E., Solis, A., Lucero, A., Maratas, S.-L. (2017). Evaluation of spatial interpolation techniques for operational climate monitoring in the Philippines. SOLA 13, 114–119. https://doi.org/10.2151/sola.2017-021.

Bassu, S., Asseng, S., Motzo, R., Giunta, F. (2009). Optimising sowing date of durum wheat in a variable Mediterranean environment. Field Crops Res. 111, 109–118. https://doi.org/10.1016/j.fcr.2008.11.002.

Deng, J.S., Wang, K., Hong, Y., Qi, J.G. (2009). Spatio-temporal dynamics and evolution of land use change and landscape pattern in response to rapid urbanization. Landscape Urban Plan. 92, 187–198. https://doi.org/10.1016/j.landurbplan.2009.05.001.

Deressa, T.T., Hassan, R.M., Ringler, C., Alemu, T., Yesuf, M. (2009). Determinants of farmers' choice of adaptation methods to climate change in the Nile Basin of Ethiopia. Glob. Environ. Change 19, 248–255. https://doi.org/10.1016/j.gloenvcha.2009.01.002.

FAO. (2012). FAO Statistical Yearbook 2012: World Food and Agriculture, Food and Agricultutr Organization of the United Nations, Rome, Italy.

Fischer, G., Van Velthuizen, H., Shah, M., Nachtergaeke, F. (2002). Global Agro-Ecological Assessment for Agriculture in the 21st Century: Methodology and Results. International Institute for Applied Systems Analysis, Laxenburg, Austria.

Fouilleux, E., Bricas, N., Alpha, A. (2017). 'Feeding 9 billion people': global food security debates and the productionist trap. J. Eur. Public Policy 24, 1658–1677. https://doi.org/10.1080/13501763.2017.1334084.

Gao, J., Yang, X., Zheng, B., Liu, Z., Zhao, J., Sun, S., Li, K., Dong, C. (2019). Effects of climate change on the extension of the potential double cropping region and crop water requirements in Northern China. Agr. Forest Meteorol. 268, 146–155. https://doi.org/10.1016/j.agrformet.2019.01.009.

He, G., Zhao, Y., Wang, L., Jiang, S., Zhu, Y. (2019). China's food security challenge: effects of food habit changes on requirements for arable land and water. J. Clean. Prod. 229, 739–750. https://doi.org/10.1016/j.jclepro.2019.05.053.

He, J., Liu, Y., Yu, Y., Tang, W., Xiang, W., Liu, D. (2013). A counterfactual scenario simulation approach for assessing the impact of farmland preservation policies on urban sprawl and food security in a major grain-producing area of China. Appl. Geogr. 37, 127–138. https://doi.org/10.1016/j.apgeog.2012.11.005.

Hutchinson, M., Xu, T. (2013). ANUSPLIN Version 4.4. Australian National University, Canberra, Australia.

Jiang, H., Hu, H., Zhong, R., Xu, J., Xu, J., Huang, J., Wang, S., Ying, Y., Lin, T. (2019). A deep learning approach to conflating heterogeneous geospatial data for corn yield estimation: a case study of the US corn belt at the county level. Glob. Chang. Biol. https://doi.org/10.1111/gcb.14885.

Jiang, Y.L., Wang, X.H., Ti, J.S., Lu, Z., Yin, X.G., Chu, Q.Q., Lei, Y.D., Chen, F. (2020a). Assessment of winter wheat water-saving potential in the groundwater overexploitation district of the North China Plain. Agron. J., 112: 44–55. https://doi.org/10.1002/agj2.20041.

Jiang, Y.L., Lu, Z., Li, S., Lei, Y.D., Yin, X.G., Chu, Q.Q., Chen, F. (2020b). Large-scale and high-resolution crop mapping in China using Sentinel-2 satellite imagery. Agriculture., 10, 433. https://doi.org/10.3390/agriculture10100433.

Keating, B.A., Carberry, P.S., Hammer, G.L., Probert, M.E., Robertson, M.J., Holzworth, D., Huth, N.I., Hargreaves, J.N.G., Meinke, H., Hochman, Z., McLean, G., Verburg, K., Snow, V., Dimes, J.P., Silburn, M., Wang, E., Brown, S., Bristow, K.L., Asseng, S., Chapman, S., McCown, R.L., Freebairn, D.M., Smith, C.J. (2003). An overview of

APSIM, a model designed for farming systems simulation. Eur. J. Agron. 18, 267–288. https://doi.org/10.1016/S1161-0301(02)00108-9.

Li, Z., Liu, Z., Anderson, W., Yang, P., Wu, W., Tang, H., You, L. (2015). Chinese rice production area adaptations to climate changes, 1949-2010. Environ. Sci. Technol. 49, 2032–2037. https://doi.org/10.1021/es505624x.

Li, Z., Yang, P., Tang, H., Wu, W., Yin, H., Liu, Z., Zhang, L. (2014). Response of maize phenology to climate warming in Northeast China between 1990 and 2012. Reg. Environ. Change 14, 39–48. https://doi.org/10.1007/s10113-013-0503-x.

Liu, J., Kuang, W., Zhang, Z., Xu, X., Qin, Y., Ning, J., Zhou, W., Zhang, S., Li, R., Yan, C., Wu, S., Shi, X., Jiang, N., Yu, D., Pan, X., Chi, W. (2014). Spatiotemporal characteristics, patterns, and causes of land-use changes in China since the late 1980s. J. Geogr. Sci. 24, 195–210. https://doi.org/10.1007/s11442-014-1082-6.

Liu, J., Shanguan, D., Liu, S., Ding, Y. (2018a). Evaluation and hydrological simulation of CMADS and CFSR reanalysis datasets in the Qinghai-Tibet Plateau. Water 10, 513. https://doi.org/10.3390/w10040513.

Liu, X.H., Han, X.L. (1987). China's Multi-Cropping. Beijing Agricultural University Press, Beijing.

Liu, Z., Hubbard, K.G., Lin, X., Yang, X. (2013). Negative effects of climate warming on maize yield are reversed by the changing of sowing date and cultivar selection in Northeast China. Glob Chang Biol 19, 3481-3492.

Liu, Z., Yang, P., Tang, H., Wu, W., Zhang, L., Yu, Q., Li, Z. (2015). Shifts in the extent and location of rice cropping areas match the climate change pattern in China during 1980–2010. Reg. Environ. Change 15, 919–929. https://doi.org/10.1007/s10113-014-0677-x.

Liu, Z., Yang, X., Lin, X., Gowda, P., Lv, S., Wang, J. (2018b). Climate zones determine where substantial increases of maize yields can be attained in Northeast China. Clim. Change 149, 473–487. https://doi.org/10.1007/s10584-018-2243-x.

Lobell, D.B., Schlenker, W., Costa-Roberts, J. (2011). Climate trends and global crop production since 1980. Science 333, 616–620. https://doi.org/10.1126/science.1204531.

Lu, D., Wang, Y., Yang, Q., He, H., Su, K. (2019). Exploring a moderate fallow scale of cultivated land in China from the perspective of food security. Int. J. Environ. Res. Public Health 16. https://doi.org/10.3390/ijerph16224329.

Olesen, J., Jensen, T., Petersen, J. (2000). Sensitivity of field-scale winter wheat production in Denmark to climate variability and climate change. Clim. Res. 15, 221–238. https://doi.org/10.3354/cr015221.

Olesen, J.E., Bindi, M. (2002). Consequences of climate change for European agricultural productivity, land use and policy. Eur. J. Agron. 16, 239–262. https://doi.org/10.1016/S1161-0301(02)00004-7.

Olesen, J.E., Trnka, M., Kersebaum, K.C., Skjelvåg, A.O., Seguin, B., Peltonen-Sainio, P., Rossi, F., Kozyra, J., Micale, F. (2011). Impacts and adaptation of European crop production systems to climate change. Eur. J. Agron. 34, 96–112. https://doi.org/10.1016/j.eja.2010.11.003.

Plourde, J.D., Pijanowski, B.C., Pekin, B.K. (2013). Evidence for increased monoculture cropping in the Central United States. Agr. Ecosyst. Environ. 165, 50–59. https://doi.org/10.1016/j.agee.2012.11.011.

Qiu, B., Lu, D., Tang, Z., Song, D., Zeng, Y., Wang, Z., Chen, C., Chen, N., Huang, H., Xu, W. (2017). Mapping cropping intensity trends in China during 1982–2013. Appl. Geogr. 79, 212–222. https://doi.org/10.1016/j.apgeog.2017.01.001.

Robinson, L.W., Ericksen, P.J., Chesterman, S., Worden, J.S. (2015). Sustainable intensification in drylands: what resilience and vulnerability can tell us. Agr. Syst. 135, 133–140. https://doi.org/10.1016/j.agsy.2015.01.005.

Sen, P.K. (1968). Estimates of the regression coefficient based on kendall's tau. J. Am. Stat. Assoc. 63, 1379–1389. https://doi.org/10.1080/01621459.1968.10480934.

Sun, Q., Kröbel, R., Müller, T., Römheld, V., Cui, Z., Zhang, F., Chen, X. (2011). Optimization of yield and water-use of different cropping systems for sustainable groundwater use in North China Plain. Agric. Water Manag. 98, 808–814. https://doi.org/10.1016/j.agwat.2010.12.007.

Sun, S., Yang, X., Lin, X., Sassenrath, G.F., Li, K. (2018). Climate-smart management can further improve winter wheat yield in China. Agr. Syst. 162, 10–18. https://doi.org/10.1016/j.agsy.2018.01.010.

Sun, S., Yang, X., Lin, X., Zhao, J., Liu, Z., Zhang, T., Xie, W. (2019). Seasonal variability in potential and actual yields of winter wheat in China. Field Crops Res. 240, 1–11. https://doi.org/10.1016/j.fcr.2019.05.016.

Sun, S., Yang, X., Zhao, J., Chen, F. (2015). The possible effects of global warming on cropping systems in China XI. The variation of potential light-temperature suitable cultivation zone of winter wheat in China under climate change. Scientia Agricultura Sinica 48, 1926–1941.

Tao, F., Yokozawa, M., Xu, Y., Hayashi, Y., Zhang, Z. (2006). Climate changes and trends in phenology and yields of field crops in China, 1981–2000. Agr. Forest Meteorol. 138, 82–92. https://doi.org/10.1016/j.agrformet.2006.03.014.

Tao, F., Zhang, Z., Shi, W., Liu, Y., Xiao, D., Zhang, S., Zhu, Z., Wang, M., Liu, F. (2013). Single rice growth period was prolonged by cultivars shifts, but yield was damaged by climate change during 1981-2009 in China, and late rice was just opposite. Glob. Chang. Biol. 19, 3200–3209. https://doi.org/10.1111/gcb.12250.

Tong, C., Hall, C.A.S., Wang, H. (2003). Land use change in rice, wheat and maize production in China (1961–1998). Agr. Ecosyst. Environ. 95, 523–536. https://doi.org/10.1016/S0167-8809(02)00182-2.

Verburg, P.H., Mertz, O., Erb, K.-H., Haberl, H., Wu, W. (2013). Land system change and food security: towards multi-scale land system solutions. Curr. Opin. Env. Sust. 5, 494–502. https://doi.org/10.1016/j.cosust.2013.07.003.

Wang, J.-F., Zhang, T.-L., Fu, B.-J. (2016). A measure of spatial stratified heterogeneity. Ecol. Indic. 67, 250–256. https://doi.org/10.1016/j.ecolind.2016.02.052.

Wang, Q., Liu, X., Yue, T., Wang, C., Wilson, J.P. (2015). Using models and spatial analysis to analyze spatio-temporal variations of food provision and food potential across China's agro-ecosystems. Ecol. Model. 306, 152–159. https://doi.org/10.1016/j.ecolmodel.2014.12.009.

Wang, X., Li, T., Yang, X., Zhang, T., Liu, Z., Guo, E., Liu, Z., Qu, H., Chen, X., Wang, L., Xiang, H., Lai, Y. (2018). Rice yield potential, gaps and constraints during the past three decades in a climate-changing Northeast China. Agr. Forest Meteorol. 259, 173–183. https://doi.org/10.1016/j.agrformet.2018.04.023.

Wu, W., Verburg, P.H., Tang, H. (2014). Climate change and the food production system: impacts and adaptation in China. Reg. Environ. Change 14, 1–5. https://doi.org/10.1007/s10113-013-0528-1.

Xiao, D., Tao, F., Liu, Y., Shi, W., Wang, M., Liu, F., Zhang, S., Zhu, Z. (2013). Observed changes in winter wheat phenology in the North China Plain for 1981-2009. Int. J. Biometeorol. 57, 275–285. https://doi.org/10.1007/s00484-012-0552-8.

Yang, X.-G., Liu, Z.-J., Chen, F. (2011). The possible effect of climate warming on Northern limits of cropping system and crop yield in China. Agr. Sci. China 10, 585–594. https://doi.org/10.1016/S1671-2927(11)60040-0.

Yang, X., Chen, F., Lin, X., Liu, Z., Zhang, H., Zhao, J., Li, K., Ye, Q., Li, Y., Lv, S., Yang, P., Wu, W., Li, Z., Lal, R., Tang, H. (2015). Potential benefits of climate change for crop productivity in China. Agr. Forest Meteorol. 208, 76–84. https://doi.org/10.1016/j.agrformet.2015.04.024.

Yin, X., Jabloun, M., Olesen, J.E., Öztürk, I., Wang, M., Chen, F. (2016a). Effects of climatic factors, drought risk and irrigation requirement on maize yield in the Northeast Farming Region of China. Journal of Agricultural Science, 154(07), 1171-1189.

Yin, X., Olesen, J.E., Wang, M., Kersebaum, K.-C., Chen, H., Baby, S., Öztürk, I., Chen, F. (2016b). Adapting maize production to drought in the Northeast Farming Region of China. European Journal of Agronomy, 77, 47-58.

Yin, X., Olesen, J.E., Wang, M., Öztürk, I., Chen, F. (2016c). Climate effects on crop yields in the Northeast Farming Region of China during 1961–2010. Journal of Agricultural Science, 154(07), 1190-1208.

Yin, X., Olesen, J.E., Wang, M., Öztürk, I., Zhang, H., Chen, F. (2016d). Impacts and adaptation of the cropping systems to climate change in the Northeast Farming Region of China. European Journal of Agronomy, 78, 60-72.

Zhao, J., Yang, X., Sun, S. (2018). Constraints on maize yield and yield stability in the main cropping regions in China. Eur. J. Agron. 99, 106–115. https://doi.org/10.1016/j.eja.2018.07.003.

Zhu, W., Zhang, X., Zhang, J., Zhu, L. (2019). A comprehensive analysis of phenological changes in forest vegetation of the Funiu Mountains, China. J. Geogr. Sci. 29, 131–145. https://doi.org/10.1007/s11442-019-1588-z.

FIGURE LEGENDS

Figure 1. The above and below blue lines represent the northern limits of China's cropping systems for the double-cropping system (DCS) and triple-cropping system (TCS) adapted in the 1980s, respectively. The black dots represent the distribution of weather stations from 1961 to 2016, and the red and green dots indicate the phenological observation sites of DCS and TCS, respectively, from 2010 to 2012.

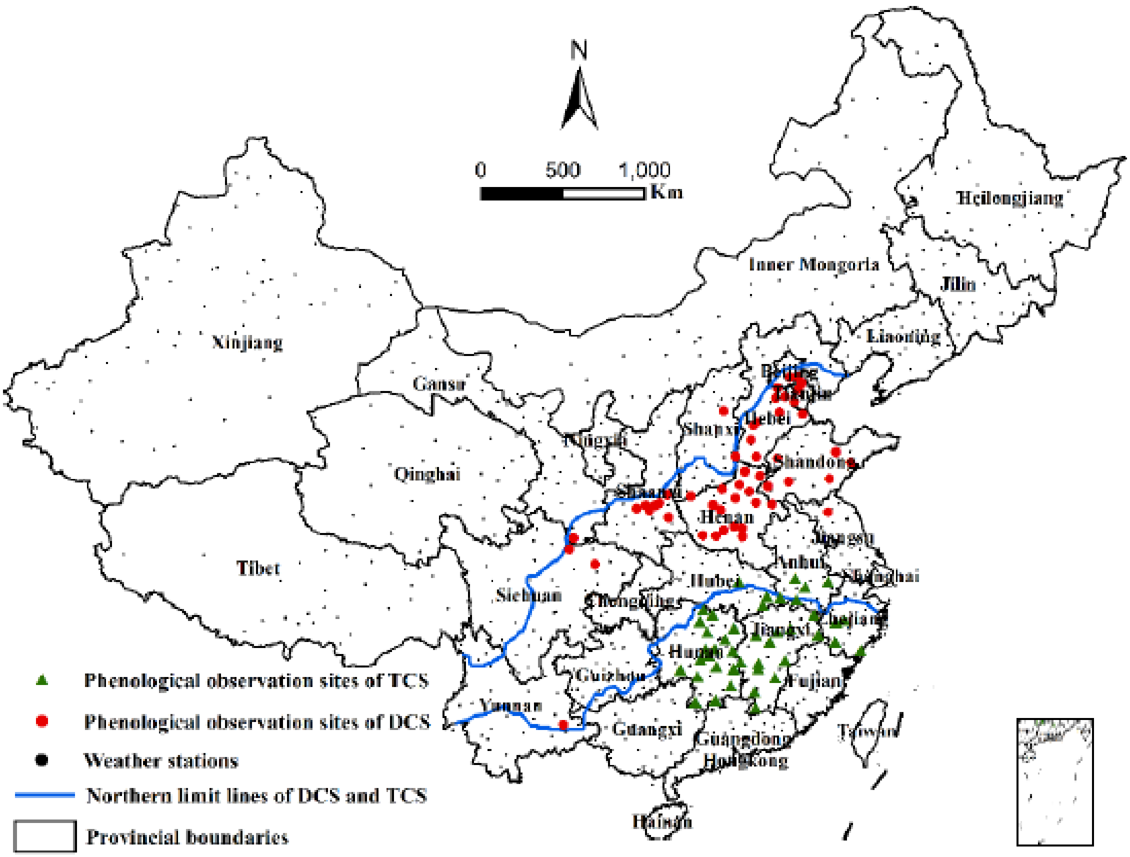


Figure 2. Trends of mean accumulated temperature above 0°C at weather stations in China from 1961 to 2016.

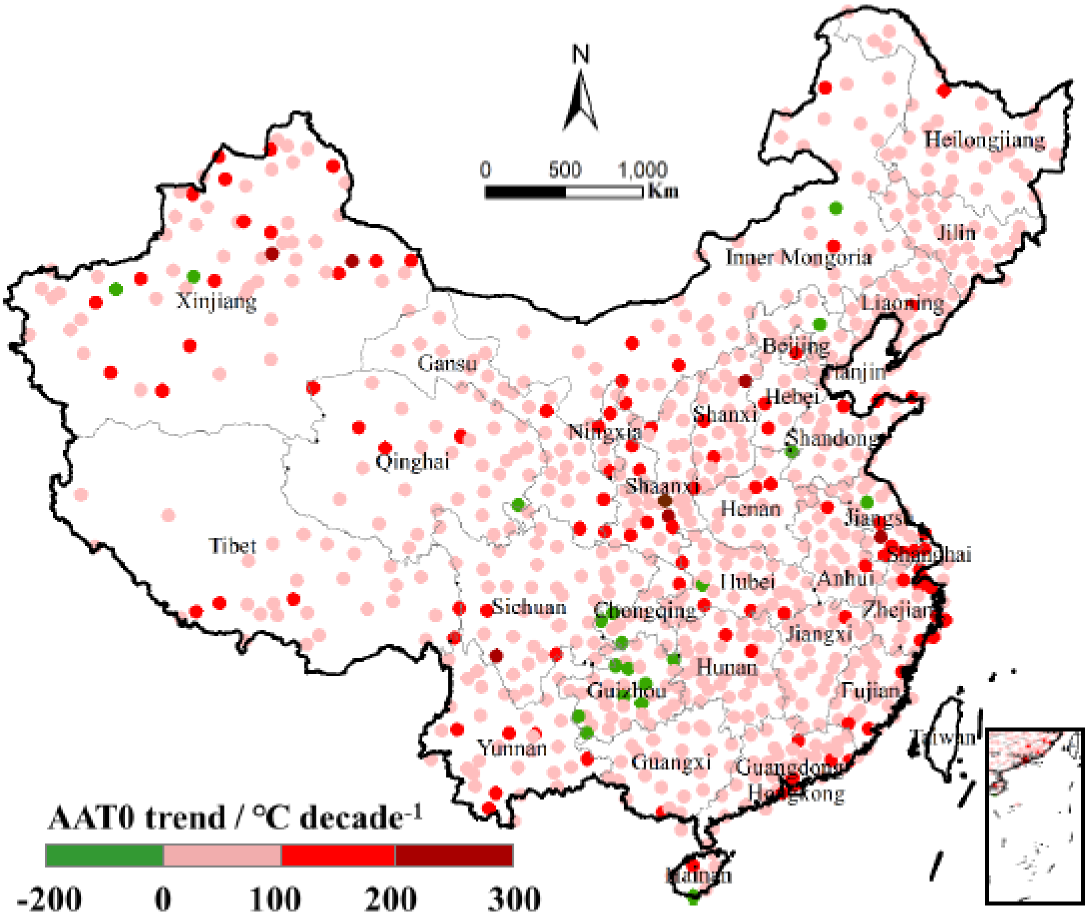


Figure 3. Accumulated temperature of double-cropping system (DCS) and triple-cropping system (TCS) at phenological observation sites in the period of 1961-1980 (red lines) and 1981-2016 (blue and yellow boxes). X represents the average value of each box.

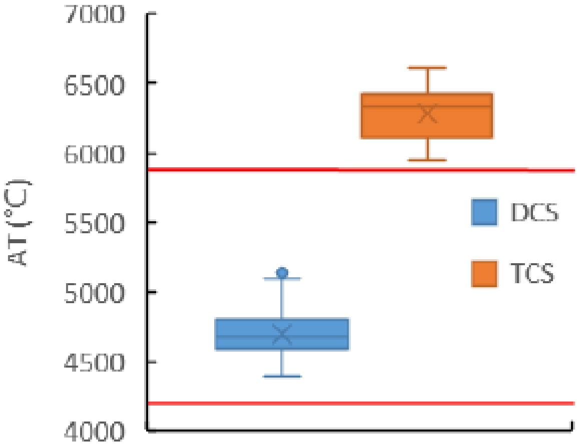


Figure 4. Changes in the northern limits for the double-cropping system (DCS) and triple-cropping system (TCS) in China during the periods of 1960-1980 (red lines) and 1981-2016 (blue lines). The bottom panel shows the changes in the major provinces covered by the northern limit lines.

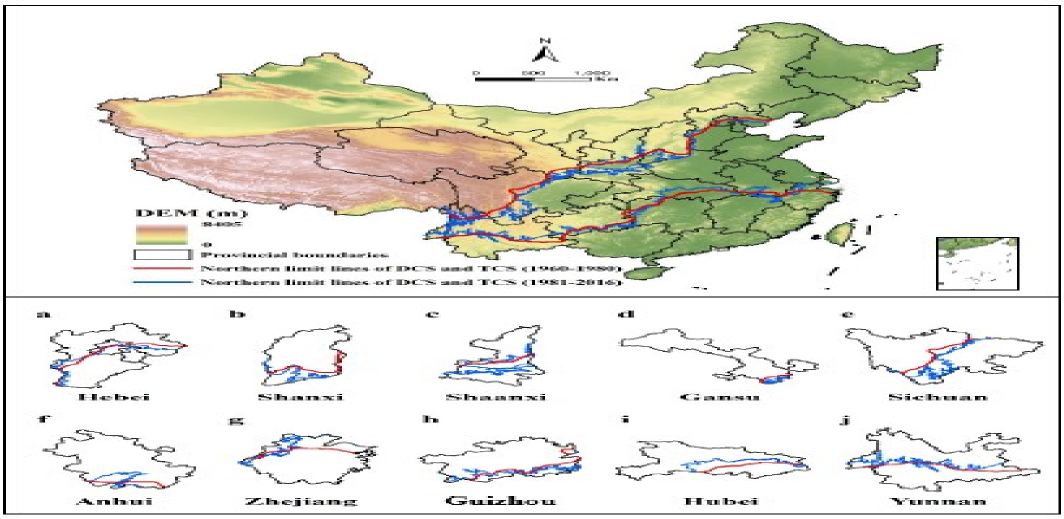


Figure 5. The distribution of multiple cropping systems and transition areas in China. The area between the minimum and average accumulative temperatures during the crop growing season was defined as the transition area.

Figure 6. Percentages of crop planting area (%) for multiple cropping systems during the periods of 1961-1980 (P1) and 1981-2016 (P2) in the major provinces covered by the northern limit lines. The pie chart on the top represents the changes in crop planting areas (%) for the single-cropping system (blue), double-cropping system (red) and triple-cropping system (green) during the two periods.

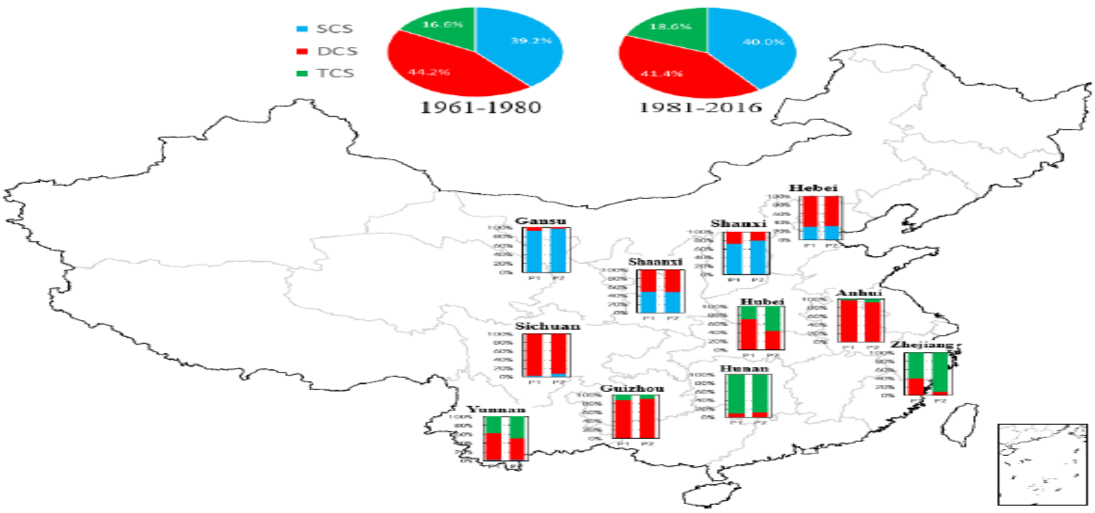


Figure 7. The actual distribution of multiple cropping area (a) and late-rice cropping area (b) in 2015; the blue lines represent the northern limit lines of the DCS and TCS in the period of 1981-2016.

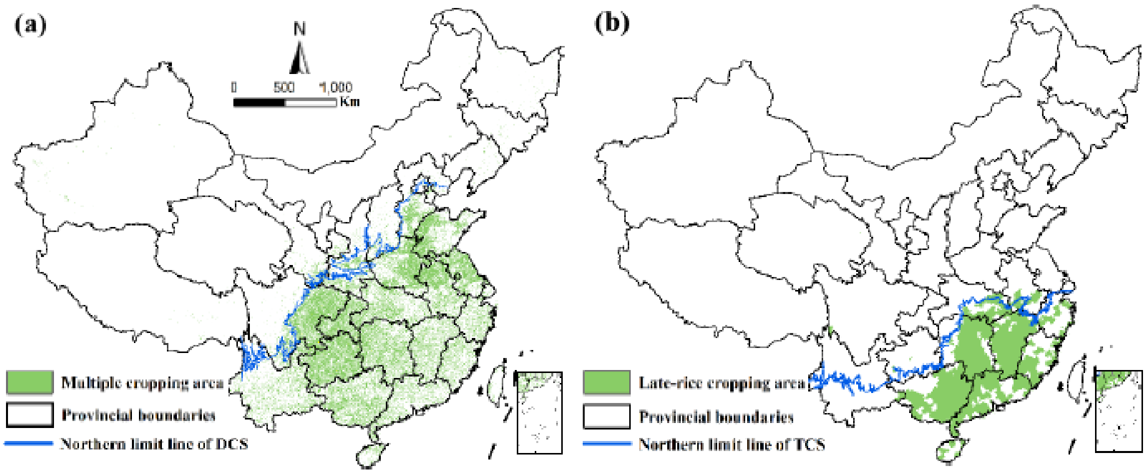
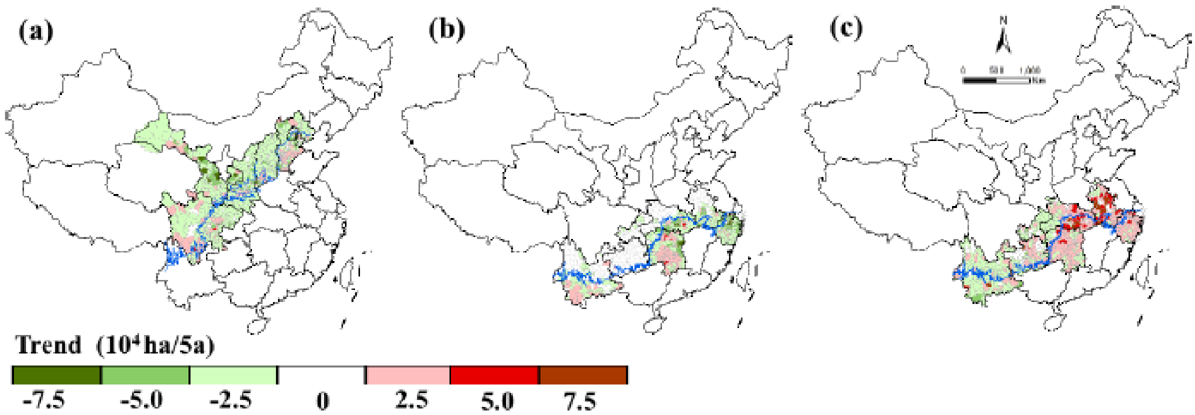


Figure 8. The spatial changes in winter wheat (a), late-rice (b) and single-rice (c) sown area around the transition area from 1985 to 2015. Blue lines represent the northern limit line of the DCS and TCS in the period of 1981-2016.



TABLES

Table 1 Temporal changes of the average cumulative mean temperature during the growing period of each type of crop in the past two decades.

Crop type	Year/℃					Trend
	1995	2000	2005	2010	2015	℃/a
Summer-maize	2459.4	2458.2	2530.4	2538.1	2525.1	4.24
Winter-wheat	2084.4	2182.5	2122.5	2220.8	2135.7	3.45
Early-rice	2540.5	2516.6	2534.5	2579.4	2584.8	3.94
Late-rice	3101.6	3112.5	3135.8	3124.9	3111.2	0.14
Rape	2215.6	2486.2	2479.1	2593.9	2507.2	14.45

Table 2 Changes of the cumulative temperature above 0°C during the crop growing period for multiple cropping systems in China.

Period	Cropping system		
	Single-cropping	Double-cropping	Triple-cropping
1961-1980	<4000	>4000-4200	>5900-6100
1981-2016	<4400	>4400-4700	>6000-6200

Note: data during the period of 1961-1980 were quoted from (Liu and Han, 1987); data during the period of 1981-2016 were calculated by current crop varieties under the standardized definition.