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Impacts of climatic warming on cropping system borders of China and potential adaptation strategies for regional agriculture development

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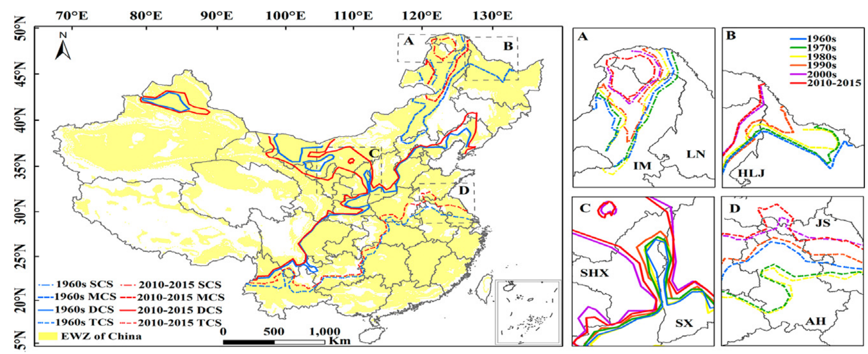
HIGHLIGHTS

- The implication of PIMCI for regional agriculture development was explored.
- The possible factors impacting the MCI change were uncovered.
- The spatial-temporal tendency of hydrothermal conditions was analyzed.

GRAPHICAL ABSTRACT



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ABSTRACT

Climate warming and its corresponding impacts on agriculture system increasingly attach great attentions. Earlier studies more concerned the impacts of the cultivated area expansion under climate change. Yet limited knowledge is about the impacts of climate warming on the cropping index change with the shifts of cropping system border. In this study, we used climatic data (1961–2015) to firstly investigate impacts of warming temperature on potential cropping system border expansion of China, and further used agricultural statistical data and satellite-based land use data to analyze the response of current land system to potential cropping system border expansion. Results of this study indicated that obviously advanced SDT10 and prolonged EDT10 contributed to the 88.4% regions of increased AAT10 at the past half century. Moreover, the northward expansion of the suitable cultivated areas in different cropping systems provided advantages for potential multiple cropping index (PMCI) improvement. Unfortunately, this study found that a significantly declined multiple cropping index (MCI) was observed in the peri-urban regions and the provinces with large out-migration of agriculture labor. The evidently increased MCI was only greatly observed in Xinjiang province. Besides, the potential increment of multiple cropping index (PIMCI) for different cropping system border expansion regions presented a rising trend and reached 53.6% in 2015 due to warming climate. Particularly, the significantly increased PIMCI was observed in the Loess Plateau, the Inner Mongolia, the Middle-lower Yangtze Plain, Northeast China Plain, Southern China and Beijing-Tianjin-Hebei Metropolitan Region. However, the response of current land system to the changes of PMCI and PIMCI was not timely. Based on the findings of our study, some potential agriculture development strategies were suggested by comprehensively considering regional natural conditions, agricultural production conditions and socioeconomic conditions. We hope these findings of this study could provide some valuable information for agricultural development policy decision-making.

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1. Introduction

China supplies food to ~20% of the world's population by using only 9% of the world's cultivated land (Rosegrant and Cline, 2003; FAOSTAT, 2012; Yang et al., 2015), thus grain production is an extremely important and urgent issue in China (Liu et al., 2013; Zuo et al., 2014). Being a major country for grain production, the contradiction between man and land is prominent in China in the context of rapid economic development and unprecedented urban expansion (Yang et al., 2015; Zhou et al., 2019). Although various studies have concerned the influences of climate change, natural disaster and adoption strategies on crop environment and agricultural production (Dai et al., 2015; Muhammad et al., 2018; Ilyas et al., 2020), how to improve the grain production ability in current cultivated land to meet increasing requirements of people is still a great challenge.

The impacts of climate change on food security have attracted the utmost attention worldwide (Charles et al., 2010; Jin et al., 2017). Agriculture is one of the most sensitive fields to the climate change (Dai et al., 2015; Tao et al., 2006; Liu et al., 2010b). On account of warming temperature, climate change have largely affected the agricultural production environment, cropping distribution patterns, cropping intensity and crop yield (Yang et al., 2015; Xu et al., 2017). Hydrothermal conditions are vital factors for crop growth, many studies have reported the relationships between agricultural production and climate variables in the context of global warming (Tubiello et al., 2000; Liu et al., 2013; Yang et al., 2015; Abbas et al., 2017; Meng et al., 2017). For instance, Tubiello et al. (2000) indicated that climate warming would accelerate crop development, shorten crop growth duration; however, considering the high summer temperature and water resource limitation in some regions, climate warming might have negative impact on crop production and possibly reduce crop yield. Besides, the original crop varieties and planting dates might be unable to adapt the warming temperature, and then leaded to negative effects on agricultural production (Hu et al., 2017; Meng et al., 2017).

Fortunately, climatic warming also improves the thermal conditions in some regions and probably results in expanding northwards of different cropping systems, which will provide the potential for increasing grain production (Yang et al., 2011; Zhang et al., 2013; Yang et al., 2015; Liu et al., 2019). As we know, expanding cultivated area and improving land intensive utilization (such as increasing cropping intensity) are two common modes to increase grain production (Gao and Liu, 2011; Shi et al., 2014; Zuo et al., 2014; Yan et al., 2019). For example, Gao and Liu (2011) found the rice paddy expansion with nearly 6 times in Heilongjiang Province of China was the result of the average temperature rising more than 2 °C in most regions during the past 50 years. Shi et al. (2014) analyzed the hydrothermal condition change for the period of 1970–2008 in northern China, and found that cropland reclamation increased significantly due to the climatic warming. Yang et al. (2015) indicated that the northern shifts of multiple cropping systems resulted in about 8 million ton increment of three major crops from 1981 to 2010, which had positively impact on grain production in China. These studies focused on the potential for increasing grain production due to the westward and northward expansion of different cropping systems.

Meanwhile, improving cropping intensity is also an effective solution for crop yield under climatic warming (Liu et al., 2013; Dias et al., 2016; Meng et al., 2017; Wu et al., 2018; Yan et al., 2019). Multiple cropping index (MCI), potential multiple cropping index (PMCI) and potential increment of multiple cropping index (PIMCI) are generally used to comprehensively evaluate cropping intensity (Liu et al., 2013; Zhang et al., 2013; Zuo et al., 2014; Yan et al., 2019). For example, Yan et al. (2019) tracked the spatial-temporal change of MCI in China during 2000–2015 based on remote sensing data at 500 m. Liu et al. (2013) analyzed the tendency of PMCI in China from 1960 to 2010 by utilizing Agricultural Ecology Zone (AEZ) model based on meteorological data. Zuo et al. (2014) generated the PIMCI distribution map of China in 2005 and suggested different strategies should be implemented to different regions for increasing grain production. These studies improved our understanding for response of cropping intensity of agriculture system to warming climate, but knowledge on the spatial-temporal distribution of PIMCI and the relationships among PIMCI change, spatial land use pattern and regional agriculture development are still limited, especially in the regions of cropping system border expansion.

Therefore, the objectives of this study were (1) to investigate spatial-temporal distribution of thermal condition change in China during 1961–2015, (2) to analyze the spatial-temporal distribution of MCI, PMCI and PIMCI at county scale, and (3) to clarify the response of current land system to PIMCI change, and attempt to provide some potential agriculture development strategies. The article was organized into various sections. After the introduction, Section 2 presented the data and methods; Section 3 presented the results and related discussion was in Section 4; the final section provided a summary of this study.

2. Data and methods

2.1. Data and preprocessing

The meteorological dataset consisted of daily air temperature and daily precipitation data with a spatial resolution of $0.25° \times 0.25°$ geographic grid for the period of 1961–2015 collected by the China Meteorological Administration (CMA). The dataset, which termed as CN05.1, was generated by interpolating 2416 meteorological stations in China (Wu and Gao, 2013). The gridded interpolation was calculated by using thin-plate smoothing splines method based on ANUSPLIN software together with the digital elevation model (DEM) as the covariate (Z. Liu et al., 2018; Wu and Gao, 2013). Considering CN05.1 data was developed from much more meteorological stations than the CN05 data with freely shared 751 observation stations, the CN05.1 data theoretically performed better on climate change exploration. Therefore, the meteorological data of China used in this study were obtained from the CN05.1. Furthermore, we also obtained daily air temperature data on a $0.75° \times 0.75°$ geographic grid for the period of 1980–2018 from ERA-Interim datasets, which were reanalysis products based on Integrated Forecast System of European Centre for Medium-Range Weather Forecasts (Dee et al., 2011). The purpose of utilizing ERA-Interim datasets was to validate the consistency of the spatial-temporal distribution of thermal conditions in China in the past decades.

This study collected county-scale agricultural datasets form the National Bureau of Statistics of China (NBSC), including China Statistical Yearbook, China Rural Statistical Yearbook, China Economical Statistical Yearbook, China Environmental Statistical Yearbook, China Regional Economic Statistical Yearbook, Development Statistical Yearbook of some provinces and relevant statistical yearbooks of each province and city. The datasets contained total sown area, total cultivated area, cropping sown area and cropland area for each county in 1995, 2005 and 2015. These statistical data were used to calculate the multiple cropping index (MCI), representing the cropping intensity in the same piece of cropland per year.

The land use data of 1 km grid in 1990, 2000, 2010 and 2015 were collected from Centre for Resource and Environmental Science Data, Chinese Academy of Sciences (Liu et al., 2014; Cui et al., 2019). Other auxiliary data included China county division map in 2009 and China Agro-climatic Zone map (http://www.resdc.cn/data.aspx?DATAID=275) (Fig. 1).

2.2. Statistics and analyses

2.2.1. Calculations of accumulated temperature-related indicators

The annual accumulated temperature above 10 °C (AAT10) was a key indicators of thermal resource used in China (Dai et al., 2015; Dong et al., 2009; Liu et al., 2019). It was the sum of the daily mean air temperatures above the critical temperature of 10 °C. Considering the influence of the random fluctuation of daily mean air temperatures, 5-

Fig. 1. Province division and Agro-climatic Zone in China.

day moving average method was used to determine the beginning dates (D_s) and the ending dates (D_e) which the temperature steadily greater than or equal to 10 °C in per year (Dai et al., 2015; Shi et al., 2014). The AAT10 was calculated using the following formula:

$$AAT10 = \sum_{i=D_s}^{D_e} T_i, T_i \geq 10 \circ C \quad (1)$$

where $\overline{T_i}$ was daily average air temperature on day i, the calculation ranged from D_s to D_e. The D_s was the SDT10 with the $T \geq 10 \circ C$, and the D_e was the EDT10 with the $T \geq 10 \circ C$. In the above formula, if $T < 10 \circ C$, we set $\overline{T} = 0$. The SDT10, EDT10 and AAT10 in this study were calculated with Python program according to the daily average air temperature from the CN05.1 datasets and the ERA-Interim analysis datasets. Furthermore, in order to analysis the spatial-temporal distribution of the hydrothermal condition more accurately, the cv2 package in the Python program was used to downscaling from $0.25° \times 0.25°$on CN05.1 dataset to $0.1° \times 0.1°$ and $0.75° \times 0.75°$on ERA-Interim analysis datasets to $0.1° \times 0.1°$, respectively.

According to the warming temperature, the distribution of the thermal condition which included SDT10, EDT10 and AAT10 would change. In our study, the period from 1961 to 2015 was divided into six different periods, i.e. 1960s (1961–1969), 1970s (1970–1979), 1980s (1981–1989), 1990s (1991–1999), 2000s (2000–2009) and 2010–2015. Firstly, the spatial distribution of each variable (SDT10, EDT10 and AAT10) was generated into six different periods, respectively. Secondly, the regression coefficient of linear regression was used to estimate the change tendency of the thermal condition distribution (Piao et al., 2011; Wang et al., 2017; Liu et al., 2019). The regression coefficient (Slope) was calculated using the following formula:

$$\text{Slope} = \frac{n\sum X_i Y_i - \sum X_i \sum Y_i}{n\sum X_i^2 - \left(\sum X_i\right)^2} \quad (2)$$

where X_i was the ith year, Y_i was the corresponding variable (SDT10, EDT10 and AAT10) in the ith year and n was the number of years. The trend analysis was carried out by Python version 3.7. Finally, student's *t*-test was used to examine the statistical significance of trends at 0.01 or 0.05 level (i.e. $p < 0.01$ or $p < 0.05$).

2.2.2. Tendency analyses of the hydrothermal condition distribution

AAT10 was an important reference indicator on the determination of agriculture climatic regions, crop planting schedules and cropping distribution patterns in China (Zheng et al., 2013; Hou et al., 2014; Dai et al., 2015; Zhang et al., 2017; Liu et al., 2019). Meanwhile, precipitation was also a critical indicator for crop variety selection, agriculture productivity and agriculture management (Wu et al., 2018; Yang et al., 2015; Liu et al., 2010b). Furthermore, as a major grain crop and a primary source of livestock feed, the research of suitable cultivated regions of maize cropping system became important under the implement of self-sufficiency national policy on maize production and the increasing demand of maize consumption (Tao et al., 2015; Xu et al., 2017). The hydrothermal indices which were generally used for single cropping system (SCS), maize cropping system (MSC), double cropping system (DSC) and triple cropping system (TSC) were given in Table 1(Zhang et al., 2017; Wu et al., 2018; Liu et al., 2019).

Considering the warming temperature, the distribution of the hydrothermal condition that included AAT10, annual temperature and annual precipitation, would change. The regression coefficients (Slope) of different hydrothermal conditions during 1961–2015 were also calculated by utilizing formula (2).

Table 1
The hydrothermal indices for different cropping systems.

Cropping system	AAT10 (°C/day)	Annual precipitation (mm)	Crop varieties
Single cropping system	≥1600	≥300	Spring wheat, soybean, millet and sorghum
Maize cropping system	≥2100	≥300	Maize
Double cropping system	≥3400	≥600	Winter wheat, maize, millet and sweet potato
Triple cropping system	≥5000	≥1200	Rice, sugarcane and rubber

2.2.3. Response evaluation of current agriculture/land system to warming climate

Multiple cropping index (MCI), potential multiple cropping index (PMCI) and potential increment of multiple cropping index (PIMCI) were used in this study to assess the change of cropping intensity. MCI referred to the cropping intensity in the same cropland area per year, representing the actual multiple cropping index (Jin et al., 2011). MCI was calculated as followed:

$$\mathrm{MCI} = A_s/A_c \tag{3}$$

where A_s was the total sown area in cropland per year and A_c was the total cropland area. Due to the lack of Statistical Yearbook in 1960s, 1970s and 1980s, the county MCI of China in 1995, 2005 and 2015 were calculated in this study. Considering the agricultural data accessibility, some counties MCI value were replaced by those counties MCI value in nearby years or the city MCI value where those counties were located.

PMCI referred to the maximum number of the cropping intensity in the same cropland area per year, representing the potential capacity of multiple cropping systems (Fan and Wu, 2004; He et al., 2016). In this study, the calculation of the PIMCI referred to the Thermal-Precipitation Model proposed by Fan and Wu (2004). Under the limit of hydrothermal condition, thermal PMCI and precipitation PMCI were firstly calculated, respectively. The thermal PMCI was based on the annual accumulated temperature above 0 °C (AAT0) value, and the calculation method of AAT0 was similar to the above formula (1) expect that the temperature parameter was replaced by 0 °C. AA0 values, which equaled to 3400 °C·day, 4200 °C·day, 5200 °C·day and 6200 °C·day, were four obvious boundary values for the prediction of thermal PMCI. Meanwhile, annual average precipitation value that equaled to 500 mm and 1200 mm were also two obvious boundary values for the prediction of precipitation PMCI. Then the PMCI value equaled to the minimum between the two values. The PMCI was calculated as following model:

$$\mathrm{PMCI} = \mathrm{MIN}(M_T, M_R) \tag{4}$$

$$M_T = \left\{ \begin{array}{c} 100 \quad T<3400 \\ (T-3400)*0.125+100 \quad 3400 \le T<4200 \\ 200 \quad 4200 \le T<5200 \\ (T-5200)*0.1+200 \quad 5200 \le T<6200 \\ 300 \quad T \ge 6200 \end{array} \right\} \tag{5}$$

$$M_R = \left\{ \begin{array}{ll} 100 \quad R<500 & \\ (R-500)*0.14+200 & 500 \le R<1200 \\ 300 & R \ge 1200 \end{array} \right\} \tag{6}$$

where M_T was the thermal PMCI, M_R was the precipitation PMCI. In our study, AAT0 and annual average precipitation of each county during 1991–1995, 2001–2005 and 2011–2015 was inputted into the model to calculate the average PMCI of each county in 1995, 2005 and 2015.

PIMCI referred the potential capacity of increasing MCI, which was the gap between PMCI and MCI. The calculation of PIMCI was as followed:

$$\mathrm{PIMCI} = \mathrm{PMCI} - \mathrm{MCI} \tag{7}$$

In our study, PIMCI of each county in 1995, 2005 and 2015 was generated from the average PMCI and the MCI of each county in the corresponding year.

3. Results

3.1. Spatial-temporal distribution of thermal condition change across China

As shown in Figs. 2–3, the temporal trends of SDT10, EDT10 and AAT10 quantitatively represented the tendency of thermal conditions in China during 1961–2015. Due to the climate change, obviously advanced SDT10, prolonged EDT10 and increased AAT10 were showed in most China ($p < 0.05$).

The 60.9% regions of China had advanced SDT10 with 0–3 days ($p < 0.05$) in the past 55 years. The regions with significantly advanced SDT10 mostly located in the Sichuan Basin and surrounding, Loess Plateau, Huang-Huai-Hai Plain and Northeast China Plain with 2.5, 2.0, 1.9 and 1.3 earlier days ($p < 0.01$), respectively. Moreover, 82.8% regions of China had obviously delayed EDT10 with 1–4 days ($p < 0.05$) during 1961–2015. The regions with obviously prolonged EDT10 mostly located in Huang-Huai-Hai Plain, Middle-lower Yangtze Plain, Northeast China Plain and Loess Plateau with 3.9, 2.7, 1,1 and 1.0 later days ($p < 0.01$), respectively.

As shown in Fig. 3d, the decadal averaged AAT10 ranged from 2656 °C·day to 2864 °C·day for the period of 1961–2015, especially during the period from 1990s to 2000s, the decade mean AAT10 significantly increased 143 °C·day. The 88.4% regions of China had increased AAT10 for the study period (55 years), of which 56.1% AAT10 showed remarkably increasing trend ranging from 200 °C·day/decade to 600 °C·day/decade. The remarkable regions of increased AAT10 were located in pan-Sichuan Basin, Northern arid and semiarid Region, Northeast China Plain and Loess Plateau with 72.9, 62.2, 61.0 and 51.7 °C·day/decade ($p < 0.01$), respectively.

3.2. Tendency of the hydrothermal condition distribution in different cropping systems

Comprehensively considering the advanced SDT10, delayed EDT10 and increased AAT10 for the period of 1961–2015, the extended warming zones of China were developed as shown in the yellow area of Fig. 4. The calculation of the extended warming zones was to take the intersection of the advanced SDT10, the delayed EDT10 and increased AAT10 from 1961 to 2015. Meanwhile, according to the thermal conditions of different cropping systems as listed in Table 1, the shifts of northern limit lines for single cropping system, maize cropping system, double cropping system and triple cropping system during 1961–2015 were showed in Fig. 4. The shifts of northern limit lines for single cropping system and maize cropping system were mainly located in the northeastern China, such as northern Heilongjiang Province and northeastern Inner Mongolia (Fig. 4). For the period of 1961–2015, the north limits of AAT10 ≥ 1600 °C·day and AAT10 ≥ 2100 °C·day moved around 135 km and 156 km, respectively. Moreover, the potential extended cultivated regions for double cropping system and triple cropping system were respectively located in the western Inner Mongolia and the Loess Plateau Region, Middle-lower Yangtze Plain and central Yunnan Province, which were similar to the significant regions of increased AAT10 in the past 55 years. Furthermore, the north

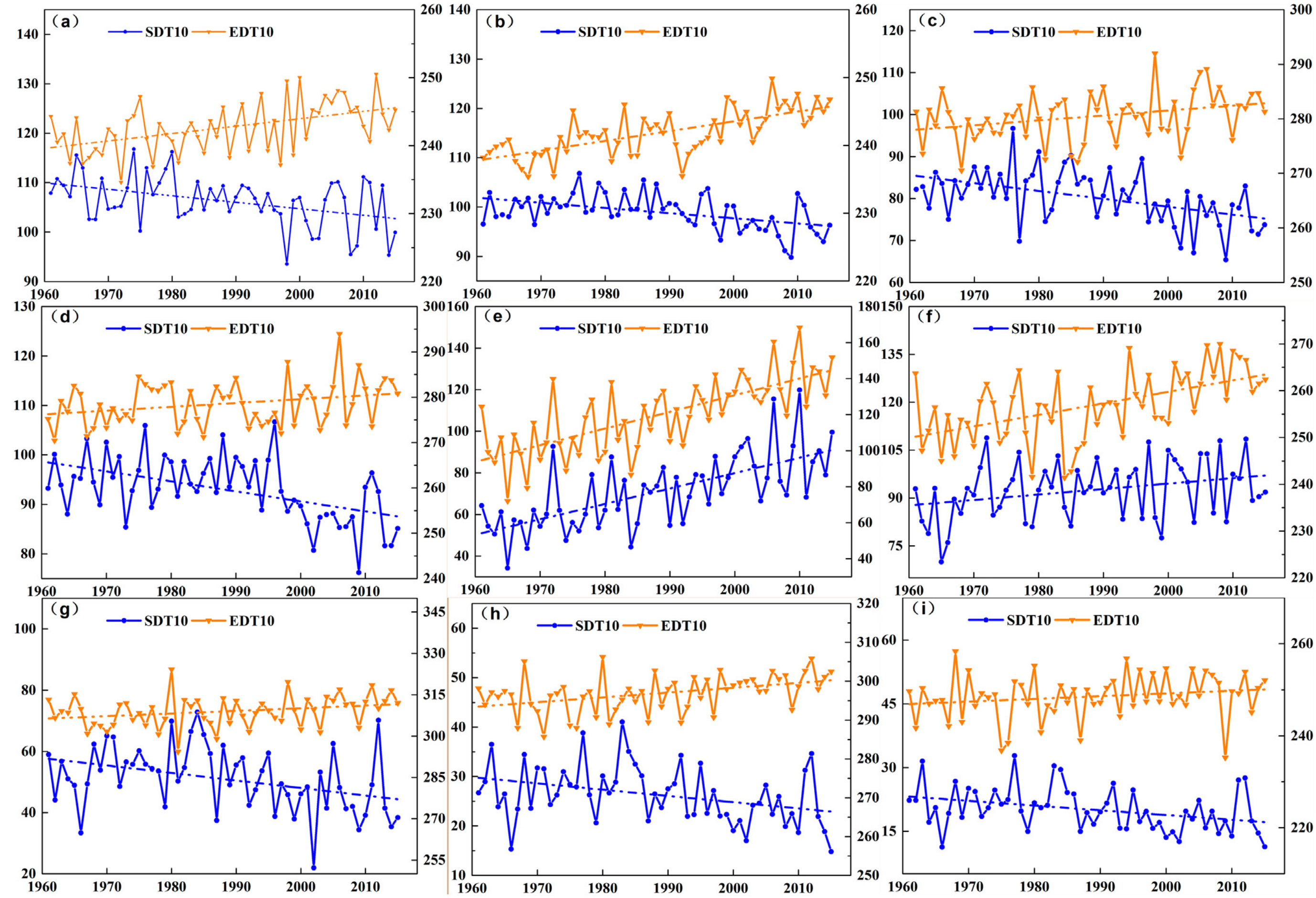

Fig. 2. Trends of SDT10 and EDT10 in China. Subfigures (a)–(i) showed the trends of SDT10 and EDT10 in Northeast China Plain (a), Northern arid and semiarid Region (b), Huang-Huai-Hai Plain (c), Loess Plateau (d), Qinghai Tibet Plateau (e), Middle-lower Yangtze Plain (f), pan-Sichuan Basin (g), Southern China (h) and Yunnan-Guizhou Plateau (i), respectively.

limits of AAT10 ≥ 3400 °C·day and AAT10 ≥ 5000a·day moved around 150 km and 185 km, respectively (Fig. 4).

To quantitatively analysis the hydrothermal condition change of the border expansion regions in different cropping systems, the trends of AAT10, annual temperature and annual precipitation of different cropping system border expansion regions during 1961–2015 were generated. As shown in Fig. 5, the tendency of hydrothermal conditions in the border expansion regions of different cropping systems was similar. In Fig. 5a, d, g and j, AAT10 performed an increased trend with 74.1–79.7 °C·day/decade ($p < 0.01$) in the extended warming zones of each cropping systems for the period of 1961–2015. Furthermore, AAT10 steadily exceeded the lower limits (i.e. 1600 °C·day, 2100 °C·day, 3400 °C·day and 5000 °C·day) of each cropping system in 2000s. In Fig. 5b, e, h and k, annual temperature presented a rising trend with 0.2–0.4 °C/decade ($p < 0.01$) in the extended warming zones of each cropping system during 1961–2015. In addition, averaged annual temperature all increased significantly after the year of 1990 by 0.5–0.8 °C. In the past 55 years, annual precipitation had no obvious variation trend in the extended warming zones of each cropping system as shown in Fig. 5c, f, i and l.

3.3. Response of current agriculture/land system to warming climate

Through analyzing the tendency of hydrothermal conditions in different cropping systems during 1961–2015, AAT10 and annual temperature performed remarkably increased trend as well as the trend of annual precipitation was relative stationary. Therefore, the hydrothermal condition change provided advantages for improving the potential multiple cropping index (PMCI). Furthermore, the spatial distribution of land use types based on the PIMCI of the border expansion regions in different cropping systems were analyzed in this study, so to express the relationship between current land systems and the potential cropping intensity from another perspective.

To evaluate the spatial-temporal distribution of the potential increment of multiple cropping index (PIMCI) in different cropping system border expansion regions, the spatial-temporal distribution of the multiple cropping index (MCI) was needed to generate firstly. As Fig. 6 shown, the MCI of potential cultivated counties firstly increased and then decreased during 1995–2015, which the average value was 138%, 144% and 133% in 1995, 2005 and 2015, respectively. According to the spatial distribution map, generally the southeastern China achieved higher MCI than the northwestern China due to the favorable hydrothermal conditions in these areas, which could provide a relatively long annual crop growth period.

Comparison of the MCI distribution in 1995, 2005 and 2015 in Fig. 6 (a-c), 29.6% counties with decreased MCI while 59.6% counties with increased MCI for the period of 1995–2005; however, 50.9% counties with decreased MCI while 33.5% counties with increased MCI for the period of 2005–2015. The MCI remarkably decreased during the past 30 years in the surrounding areas around the urban agglomeration, especially in the sprawling periphery of megalopolis, such as eastern Middle-lower Yangtze Plain (Histograms MYP of Fig. 6) and Beijing-Tianjin-Hebei Metropolitan Region. Meanwhile, the MCI of most parts of Anhui Province also significantly decreased more than 50% during 2005–2015. As shown in Fig. 6d, the proportion of different MCI in Middle-lower Yangtze Plain change from 34.5%, 18.8%, 18.3%, 23.9%

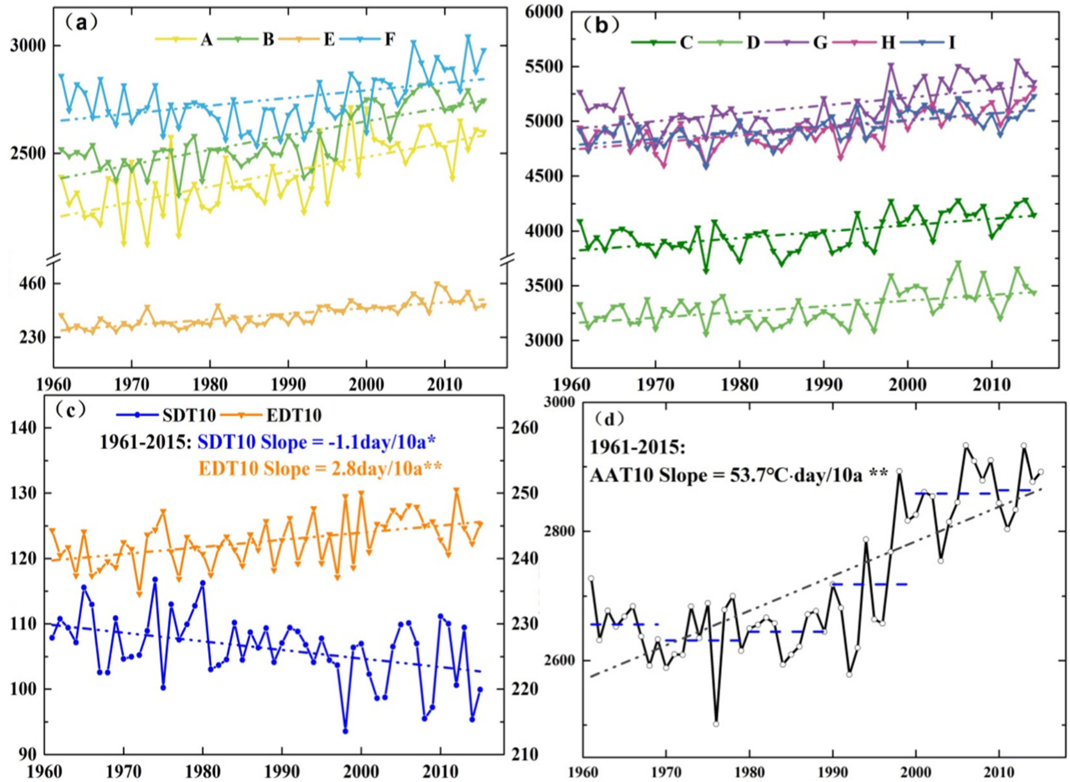

Fig. 3. Trends of thermal conditions in China. Subfigures (a)–(b) showed the trends of AAT10 in Northeast China Plain (A), Northern arid and semiarid Region (B), Huang-Huai-Hai Plain (C), Loess Plateau (D), Qinghai Tibet Plateau (E), Middle-lower Yangtze Plain (F), pan-Sichuan Basin (G), Southern China (H) and Yunnan-Guizhou Plateau (I), respectively; Subfigures (c)–(d) showed the trends of SDT10, EDT10 and AAT10 in China. The symbols ** represented the significance at the 0.01 level. The blue dashed lines in subfigure (d) represented the average of each decade.

and 4.6% in 1995 to 12.9%, 72.9%, 10.0%, 2.5% and 1.7% in 2015, the MCI of 200–250 decreased remarkably. In addition, the proportion of different MCI in Sichuan Basin and surrounding firstly increased from 13.2%, 3.5%, 26.1%, 34.5% and 22.7% in 1995 to 13.4%, 3.9%, 23.9%, 33.9% and 24.8% in 2005, and then declined to 14.6%, 17.5%, 38.5%, 16.8% and 12.6% in 2015. However, some counties of Xinjiang Autonomous Region were exception, the MCI gradually increased above 200% from 1995 to 2015. In addition, the MCI of some counties in Heilongjiang Province

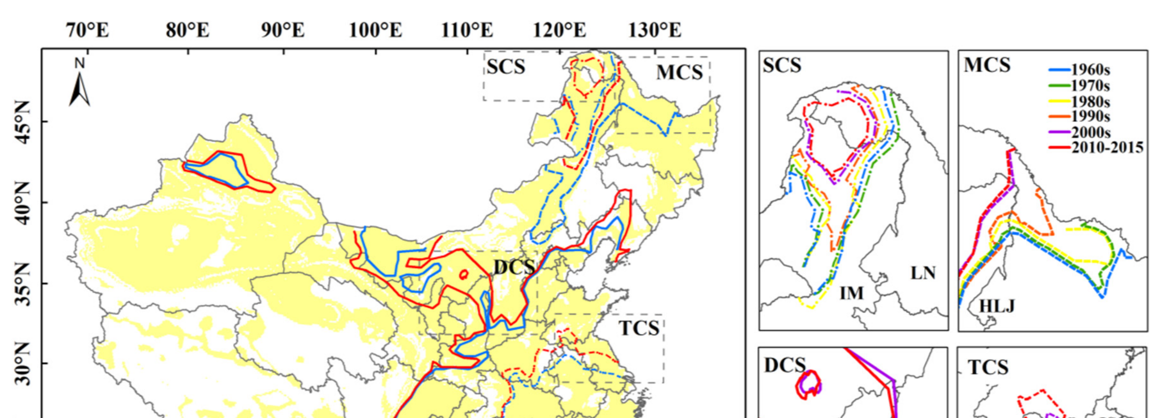

Fig. 4. Northern limit lines of potential single cropping system (SCS), potential maize cropping system (MCS), potential double cropping system (DCS) and potential triple cropping system (TCS) in 1960s (blue lines) and 2010–2015 (red lines). The yellow area represented the extended warming zones (EWZ) during 1961–2015. Subfigures showed enlarged shifts of northern limit lines for different cropping systems.

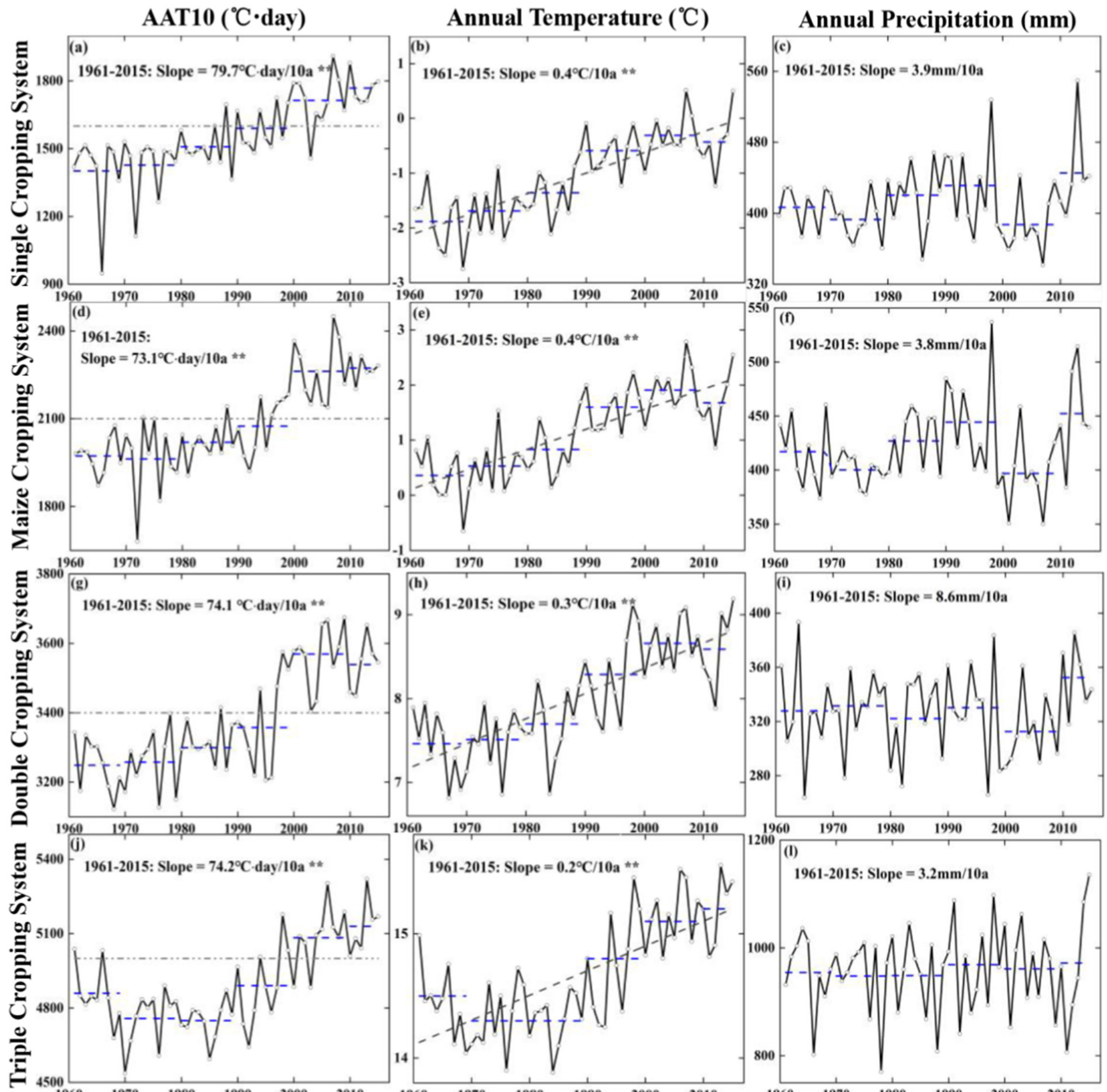

Fig. 5. Tendency of AAT10, temperature and annual precipitation related to the border expansion regions of different cropping systems. Subfigures (a)–(c), (d)–(f), (g)–(i) and (j)–(l) showed the spatial-temporal distribution of hydrothermal conditions in single cropping system, maize cropping system, double cropping system and triple cropping system, respectively. The symbols ** represented the significance at the 0.01 level. The blue dashed lines represented the average of each decade. In subfigures (a), (d), (g) and (j), the black dashed lines separately represented AAT10 value of 1600 °C·day, 2100 °C·day, 3400 °C·day and 5000 °C·day. In subfigures (b), (e), (h) and (k), the black dashed lines separately represented the trend of annual temperature in different cropping systems during 1961–2015.

also increased during 1995–2005; and the proportion of different MCI in Northeast China Plain (Fig. 3d) ranged from 60.8% and 39.1% in 1995 to 58.1% and 41.2% in 2005.

The PIMCI change in the potential cultivated regions was similar to the MCI change during 1995–2015, which the average value was 37.3%, 35.1% and 53.6% in 1995, 2005 and 2015, respectively. Generally, the southeastern China had higher PIMCI compared with the northwestern China during the past 30 years as shown in Fig. 7. Significant PIMCI increment with about 25% occurred in some counties of Loess Plateau and some region of Sichuan Province in 2015. Meanwhile, the spatial distribution of PIMCI greater than 50% ranged from scattered distribution to cluster distribution during 1995–2015 in Middle-lower Yangtze Plain. Moreover, the PIMCI was larger than 25% in some regions of Inner Mongolia during 1995–2015, and the positive PIMCI was occurred in most counties of Inner Mongolia and Northeast China Plain in the past 30 years. As shown in Fig. 7d, the value of PIMCI above 50% showed increased trend in different regions of China for the period of 1995–2015, especially in the Sichuan Basin and surrounding, Yunnan-Guizhou Plateau, Huang-Huai-Hai Plain and Loess Plateau.

As shown in Fig. 8, the mainly land use type in the border expansion counties of different cropping systems with PIMCI < 0 at 2015 was unused land, of which the proportion was 55.37%, 54.51%, 58.48% and 32.27%, respectively; and most unused land were located in Xinjiang Autonomous Region and Western Inner Mongolia. Meanwhile, the mainly land use type of the PIMCI > 0 counties at 2015 was grassland with 33.15%, grassland with 39.56%, unused land with 42.96% and cropland with 27.82% in single cropping system, maize cropping system, double cropping system and triple cropping system, respectively. Furthermore, five counties with PIMCI > 0 at 1990, 2000 and 2015 were selected to express the spatial-temporal distribution of land use types in

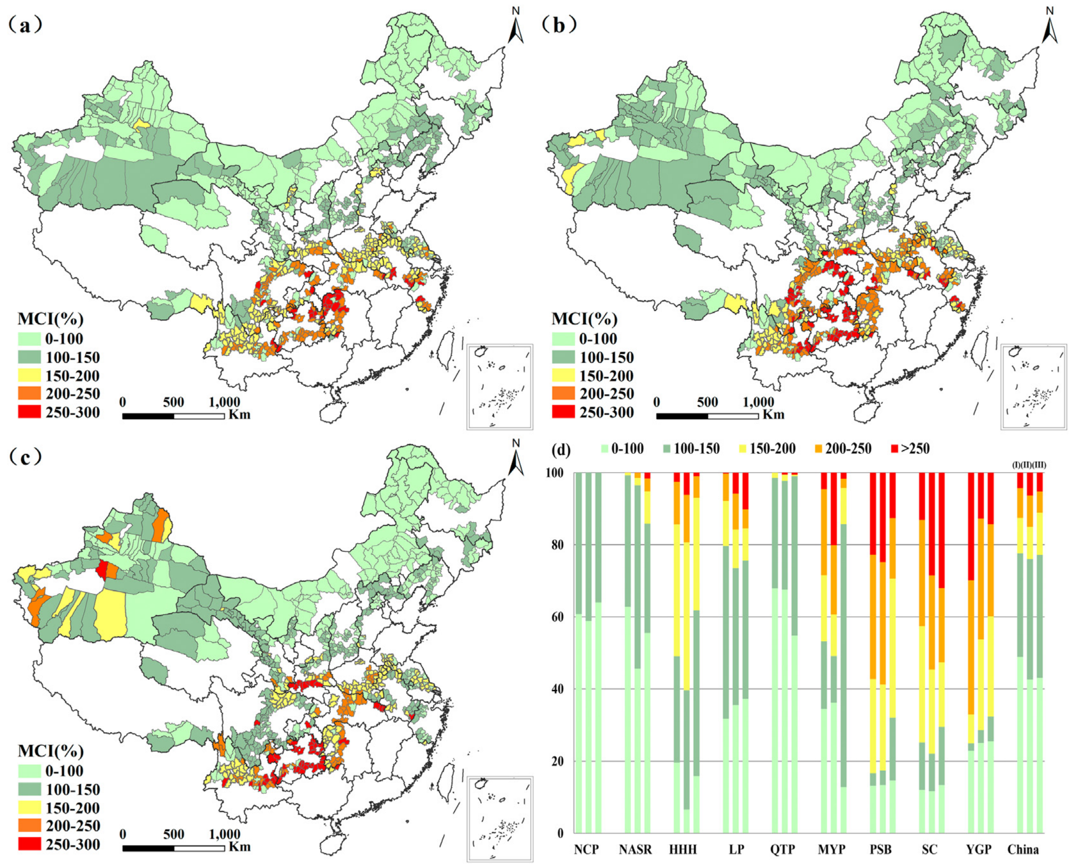

Fig. 6. Spatial-temporal distribution of MCI in China. Subfigures (a)–(c) showed the spatial distribution of MCI related to potential cultivated counties in 1995 (a), 2005 (b) and 2015 (c), respectively; subfigure (d) showed the proportions of different MCI in Northeast China Plain (NCP), Northern arid and semiarid Region (NSAR), Huang-Huai-Hai Plain (HHH), Loess Plateau (LP), Qinghai Tibet Plateau (QTP), Middle-lower Yangtze Plain (MYP), pan-Sichuan Basin (PSB), Southern China (SC), Yunnan-Guizhou Plateau (YGP) and China in 1995 (I), 2005 (II) and 2015 (III), respectively.

different cropping systems. The proportion of different land use types remained stable in 1990, 2000 and 2015, and the proportion of cropland in the counties located in triple cropping system decreased from 75.32% in 1995 to 63.78% in 2015.

4. Discussion

4.1. In comparison with results from ERA-Interim dataset

To further validate the tendency of earlier SDT10, later EDT10 and increased AAT10 during the past decades under the influence of warming temperature, spatial-temporal distributions of thermal conditions were also generated based on ERA-Interim dataset. The spatial-temporal trends of SDT10, EDT10 and AAT10 based on 1981–2018 ERA-Interim dataset were shown in Fig. S1.

In Fig. S1, 64.9% regions had advanced SDT10 with 1–4 days ($p < 0.05$) for the period of 1980–2018, which was similar to the SDT10 spatial-temporal trends of the CN05.1 dataset. The regions with obviously advanced SDT10 mainly included Sichuan Basin and surrounding, Loess Plateau, Huang-Huai-Hai Plain, Northeast China Plain and Northern arid and semiarid Region with 4.6, 4.0, 3.3, 1.6 and 1.6 earlier days ($p < 0.05$), respectively. Moreover, 63.3% regions had prolonged EDT10 with 1–3 days ($p < 0.05$) during 1981–2018, which the significant changing areas mostly located in Middle-lower Yangtze Plain, Northeast China Plain, Loess Plateau and Huang-Huai-Hai Plain with 2.6, 1.4, 1,1 and 1.0 later days ($p < 0.05$), respectively. Furthermore, Fig. S2 showed that 86.8% regions had increased AAT10 in the past 39 years, which 41.7% regions with remarkably increasing trend ranging from 200 °C·day/10a to 600 °C·day/10a, including Loess Plateau, Sichuan Basin and surrounding, Middle-lower Yangtze Plain and Northeast China Plain.

Comprehensively analyzing the spatial-temporal trends of thermal conditions in China based on 1961–2015 CN05.1 dataset and 1981–2018 ERA-Interim dataset, the conclusion of increasing heat conditions with advanced SDT10, prolonged EDT10 and increased AAT10 could be drawn. Climatic warming could not only prolong potential growing season and alter cropping intensity but also affect the spatial distribution of different cropping systems (Dong et al., 2009; Gao and Liu, 2011; Zhang et al., 2013; Shi et al., 2014).

4.2. Possible factors impacting current multiple cropping index change

The spatial variation of the MCI in the potential cultivated regions for different cropping systems during the past decades was influenced by natural conditions, socioeconomic factors, agricultural production conditions, labor attributes, agricultural policies and relevant factors (Qiu et al., 2017; Li et al., 2018; Wang et al., 2018; Liu, 2018; Yan et al., 2019; Cao et al., 2019; Grădinaru et al., 2019; Han and Song, 2019; Qiu et al., 2020). The driving factors contributing to the spatial-temporal changes of the MCI in different potential cultivated regions of different cropping systems were diverse.

In the past 30 years, the significantly declined trends of the MCI in the peri-urban regions, especially in the sprawling periphery of megalopolis, possibly attributed to the socioeconomic factors (Li et al., 2018; Wang et al., 2018; Qiu et al., 2020). Qiu et al. (2020) indicated that urbanization-induced abandonment in peri-urban regions was predominant during the past two decades, and represented that cropland abandonment process was spatiotemporally coupled with the urbanization process, particularly the emergence of high-quality cropland

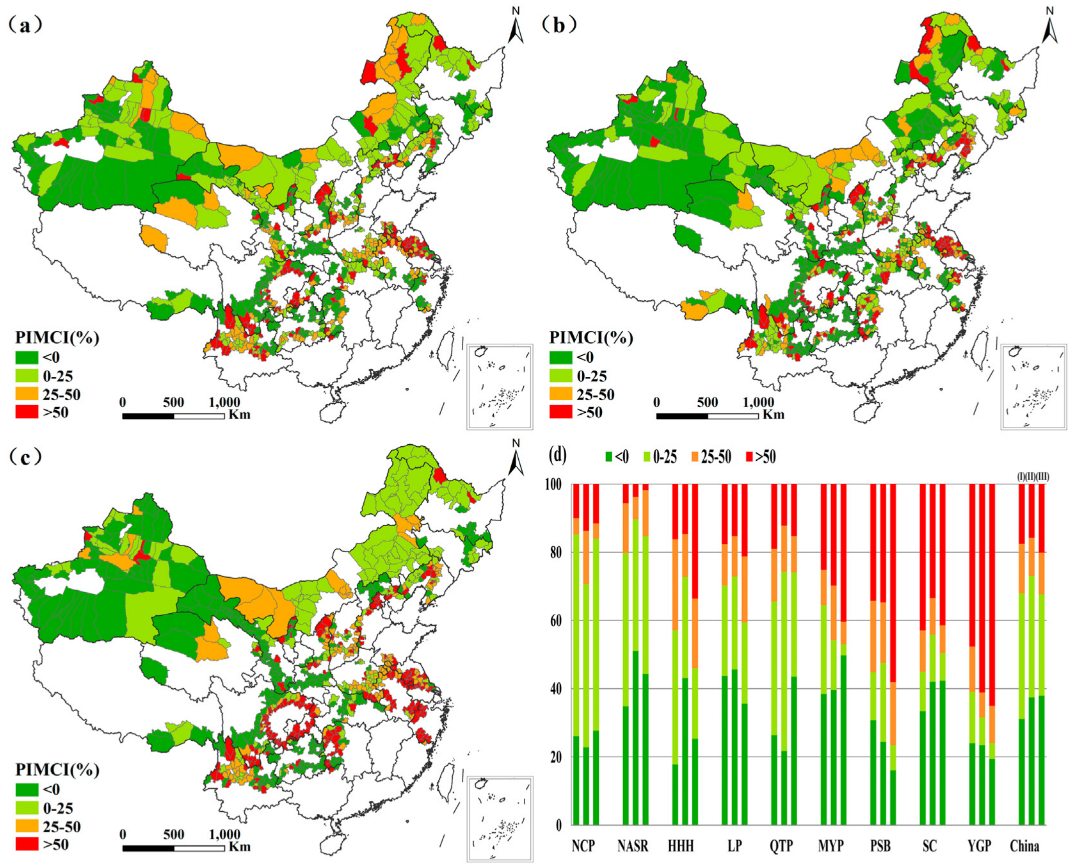

Fig. 7. Spatial-temporal distribution of PIMCI in China. Subfigures (a)–(c) showed the spatial distribution of PIMCI related to potential cultivated counties in 1995 (a), 2005 (b) and 2015 (c), respectively; subfigure (d) showed the proportions of different PIMCI in Northeast China Plain (NCP), Northern arid and semiarid Region (NSAR), Huang-Huai-Hai Plain (HHH), Loess Plateau (LP), Qinghai Tibet Plateau (QTP), Middle-lower Yangtze Plain (MYP), pan-Sichuan Basin (PSB), Southern China (SC), Yunnan-Guizhou Plateau (YGP) and China in 1995 (I), 2005 (II) and 2015 (III), respectively.

abandonment in urban surrounding regions. As shown in Fig. 6, the MCI of the eastern Middle-lower Yangtze Plain and Beijing-Tianjin-Hebei Metropolitan Region presented various degrees of declined trend, and the downward trend accelerated obviously after 2005.

Moreover, out-migration of agriculture labor was also an important driving factor caused the decreased MCI trend in some regions of China (Yan and Z, 2016; Li and Li, 2017; Y. Liu et al., 2018a; Shao et al., 2015; Xie et al., 2014). The possible reasons of declining MCI occurred in Chongqing Municipality, southeastern Sichuan Province, Anhui Province and Jiangxi Province, after 2005 (Fig. 6) were listed as followed. On the one hand, as a result of rural-to-urban population migration, the cropland and MCI decreased along with the cropland abandonment in many counties of south China, especially the low-quality cropland in hilly rural regions and the cropland in relatively less-favored locations (Cocca et al., 2012; Yan and Z, 2016; Qiu et al., 2020). On the other hand, in the mountainous regions of China, such as Chongqing Municipality, low-quality croplands and the difficulty in mechanization application were also influencing factors which would lead to the MCI declining (Shao et al., 2015; Shi et al., 2016; Li et al., 2018; Qiu et al., 2020). Moreover, the continuous aging agriculture labor would have impact on maintaining the present MCI (Li and Li, 2017; Yan et al., 2019).

Furthermore, the utilization of drip irrigation, greenhouse and agriculture mechanization remarkably boosted the agricultural production conditions and agricultural production efficiency (Xu et al., 2003; Zhang et al., 2013; Li et al., 2016). For instance, the adoption of drip irrigation in Xinjiang increased grain production under maintaining the oasis ecological environment (Li et al., 2016). The warming temperature also leaded to the cropland expansion in some counties of north China, especially in the Northeast China Plain (Liu et al., 2014, 2018a). For the period of 2000–2015, the proportion of cropland increment in the extended warming zones of single cropping system, maize cropping system and double cropping system were 17.4%, 30.5% and 70.9%, respectively. Meanwhile, the improvement of the agricultural production contributed to the increasing MCI trend in several counties of Heilongjiang Province and Xinjiang Autonomous Region during 1995–2015 (Fig. 6). Furthermore, the Chinese government implemented a series of agricultural stimulation policies in the early 21st century, including the elimination of the agricultural tax, increasing agricultural subsidies, and increasing grain price, so as to benefit farmers and increase farmers' production enthusiasm (Huang et al., 2013; Qiu et al., 2020; Yan et al., 2019). These agricultural policies also contributed to the increased MCI trends.

4.3. Implications and suggestions for regional agriculture development

As shown in Fig. 7, the remarkably increased PIMCI occurred in the Loess Plateau during 1995–2015, which provided a great potential for developing double cropping system by replacing single cropping system. A recent 3-year field-based experiment in the Yangjuangou watershed of Baota District, Yan'an city also suggested large potential for cultivating double cropping system under the impact of suitable hydrothermal conditions and optimized planting structure (Liu et al., 2017; Liu et al., 2019). Therefore, the forage planting was introduced into local agricultural production (Fig. 9), which effective promoted the development of ecological specialty industries and improved the local economy (Liu and Wang, 2019). Furthermore, since 1999, the 'Grain for Green' project had significantly improved the eco-environment in the Loess Plateau (Cao et al., 2018); and then the implement of 'Gully Consolidation and Sustainable Land Use on the Loess Plateau' project

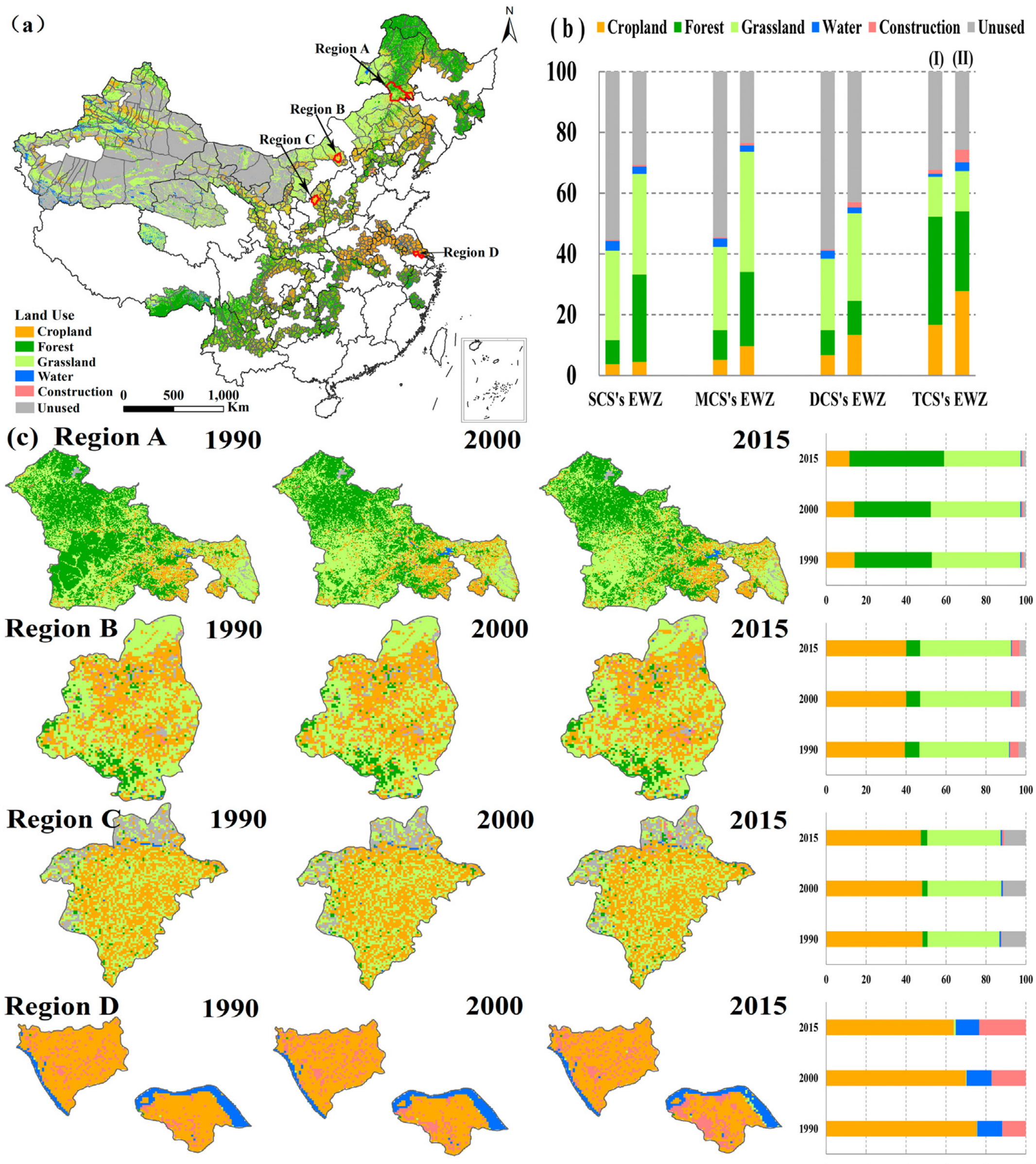

Fig. 8. Spatial distribution of land use types related to the border expansion regions of different cropping systems. Subfigure (a) showed the spatial distribution of land use types related to the border expansion regions of different cropping systems in 2015; subfigure (b) showed the proportion of different land use types related to the border expansion regions of single cropping system (SCS's EWZ), maize cropping system (MCS's EWZ), double cropping system (DCS's EWZ) and triple cropping system (TCS's EWZ) with negative PIMCI (I) and positive PIMCI (II) in 20,015, respectively; subfigure (c) showed the spatial distribution of land use types in Region A, Region B, Region C, Region D with positive PIMCI in 1990, 2000 and 2015, and the histograms showed the proportion of different land use types in the counties at the corresponding year.

after 2012 obviously enhanced grain production, protected ecological environment and guaranteed household livelihoods (Liu et al., 2017; Liu and Wang, 2019). Under the background of increasing PIMCI, reasonable optimized planting structure and raising cropping intensity would have significantly impact on eco-environmental protection, grain production increment and rural income growth.

Furthermore, many counties in Inner Mongolia had positive PIMCI for the period of 1995–2015; excepting the mainly land use types of some counties located in the western Inner Mongolia were unused land and grassland (Fig. 8), the other counties had significantly potential for increasing cropping intensity (Fig. 7). As Inner Mongolia was controlled by the arid and semi-arid climate and its ecological environment in some regions was very fragile, therefore the shortage of water resource and low-quality farmland might be a constraint on large-scale agriculture development (Zhou et al., 2007). However, the application of modern agricultural technologies had positive effective effect on improving grain production. For instance, sandy land consolidation engineering by applying 'structural consolidation' to improve sandy land structure and modern agricultural development which experimented in Yulin City had remarkably improved cropland quality, activated cropland productivity, optimized ecological environment and increased local economic development (Y. Liu et al., 2018c; Liu and Wang, 2019); the application of drip irrigation technology and greenhouse produced noteworthy grain production, economic and ecological benefits in several regions of Xinjiang Autonomous Region (Li et al., 2016). Therefore, through constructing water conservancy facilities, conducting soil improvement and utilizing modern agricultural technologies, the limitation of water resource and desertification might be resolved in Inner Mongolia, so as to improve the efficiency of cropland production, develop newly agricultural and animal husbandry, enhance ecological functions and alleviate regional rural socio-economic revitalization.

Fig. 9. Farmland landscape in Baota District, Yan'an City.

The PIMCI of the Middle-lower Yangtze Plain and Beijing-Tianjin-Hebei Metropolitan Region presented gradually increasing and gathering trend in the past 30 years (Fig. 7). However, the actual cropping intensity was difficult to improve as the result of the process of rapid urbanization and the loss of abundant agricultural labor since the early 21st century (Grădinaru et al., 2015; Li et al., 2018). As shown in the counties of region D on Fig. 8a, cropland proportion gradually declined during 1995–2015, which was similar to Qiu et al. (2020) found, some high-quality cropland in the sprawling surroundings of megalopolis even abandoned due to the demand of urban expansion and economic development. Meanwhile, the aging agricultural labor and low-quality cropland in the hilly regions also had passive influence on improving cropping intensity (Shi et al., 2016; Li and Li, 2017; Yan et al., 2019). Under this background, practical policies and effective measures were needed to balance the relationships among grain production, urban development and eco-environmental diversity, and optimizing the distribution of high-quality cropland among peri-urban and rural regions. On the one hand, considering the local conditions, the government should encourage the development of urban agriculture, leisure agriculture, tour agriculture, marine agriculture and other modern agricultural parks in the peri-urban regions (Gong et al., 2012; Y. Liu et al., 2018b). Meanwhile, the local government should pay attention to the combination of the refined processing of agricultural products and cold chain logistics technology so as to promote agriculture industrialization (Y. Liu et al., 2018b). On the other hand, farmland transfer policy and the utilization of small-scale agricultural mechanization would have positive effect on steadily increasing agricultural production capacity and household income in the hilly regions (Liu et al., 2010a; Long et al., 2010; Shao et al., 2015).

5. Conclusions

This study firstly analyzed the tendency of climatic condition distribution in different agricultural zones and cropping systems of China, and then investigated the spatial-temporal distribution of MCI, PMCI and PIMCI at the county-level scale, and further clarified the response of current land system to PIMCI change. Results indicated that current land system did not timely respond the changes of PIMCI. Due to the advanced SDT10 , prolonged EDT10 and increased AAT10 in the 60.9%, 82.8% and 88.4% regions of China, the north limits of single cropping system, maize cropping system, double cropping system and triple cropping system were moved around 135 km, 156 km, 150 km and 185 km, respectively. The PIMCI of the border expansion regions in different cropping systems presented rising trend and reached 53.6% in 2015. The significantly increased PIMCI was observed in the Loess Plateau, most regions of Inner Mongolia, the Middle-lower Yangtze Plain, Northeast China Plain, Southern China and Beijing-Tianjin-Hebei Metropolitan Region. Comprehensively considering the natural conditions, agricultural production conditions and socioeconomic conditions, some potential strategies were suggested to different regions for improving land use efficiency, boosting regional development and protecting ecological environment. We hope the findings and potential strategies would provide valuable informational support for making agricultural development policy and improving rural socio-economic development. Besides, quantitatively analyzing the impact of socioeconomic factors, such as labor income, gross agricultural machinery and irrigation cropland area, will be helpful for providing a more comprehensive picture for our understanding of the dynamic PIMCI change.

CRediT authorship contribution statement

Xueqi Liu: Conceptualization, Data resource, Methodology, Software, Writing original manuscript;

Yansui Liu: Conceptualization, Supervision, Funding acquisition, Editing manuscript;

Zhengjia Liu: Conceptualization, Data resource, Methodology, Funding acquisition, Editing manuscript;

Zongfeng Chen: Data resource, Data processing.

Declaration of competing interest

We declare that we have no financial and personal relationships with other people or organizations that can inappropriately influence our study, there is no professional or other personal interest of any nature or kind in any product, service and company that could be constructed as influencing the manuscript entitled Impacts of climatic warming on cropping system borders of China and potential adaptation strategies for regional agriculture development.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.scitotenv.2020.142415.

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