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RESEARCH ARTICLE

# Extended warm temperate zone and opportunities for cropping system change in the Loess Plateau of China

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Thermal condition changes largely affect crop phenology, cropping systems and crop field. In this study, we used long-term (1961–2015) annual accumulated temperature ≥10 °C (AAT10) derived from daily gridded air temperature to investigate the potential implication of AAT10 changes for regional agriculture development in the Loess Plateau (LP). Results showed that an elevation-dependent spatial pattern of AAT10 was observed. Southeastern LP with low elevation had higher AAT10 and western LP with high elevation had lower AAT10. Across the LP, the start date of 5-day moving average temperature ($\overline{T}$) ≥10 °C (SDT10) showed significantly advanced trends ($p < 0.05$), and length of durations of $\overline{T} \geq 10$ °C (LDT10) and AAT10 both showed significantly increased trends ($p < 0.05$) in the past 55 years. Yet significantly delayed end date of $\overline{T} \geq 10$ °C (EDT10) was not observed. Compared with EDT10, STD10 contributed more to variations of LDT10 ($R^2 = 0.76$, $p < 0.01$) and AAT10 ($R^2 = 0.64$, $p < 0.01$). Besides, this study found that increased temperature in corresponding LDT10 was also responsible for AAT10 increase. Spring temperature contributed more to AAT10 increase relative to autumn and summer temperature. Importantly, area of warm temperate zone (AAT10 ranging 3,400–4,500 °C·day) across LP increased from 21.0% in 1960s to 50.3% in 2000–2015 due to climate change. These findings suggest that most LP, especially in regions with good soil conditions and sufficient water resources, had a large potential to develop new cropping systems with two crops per year, which will be helpful for optimizing regional land use and providing decisions on agricultural management.

KEYWORDS

annual accumulated temperature, climate warming, cropping systems, land use, Loess Plateau

## 1 | INTRODUCTION

Climate change has largely increased surface air temperature at the regional and global scales. Air temperature of the terrestrial surface has increased 0.65 °C since 1880 (IPCC, 2013; Ma *et al*., 2017). In China, surface air temperature has increased 1.1 °C in the past five decades (Tang and Ren, 2005; Ding *et al*., 2007; Dong *et al*., 2009). Warming temperature and its effect cause high attentions of many studies. Recently, some studies have reported that warming temperature largely affects crop growth (Tubiello *et al*., 2000; Jalota *et al*., 2012; Abbas *et al*., 2017; Hu *et al*., 2017). For example, using observed data of 82 agrometeorological stations in China, Hu *et al*. (2017) suggested that climate warming in China shortened rice growth duration length and advances in the planting date or adoptions of new cultivars with longer growth duration length were feasible adaptations in the context of climate change. The study of Abbas *et al*. (2017) indicated that warming temperature advanced the dates of maize anthesis and maturity and also shortened their phases. Thus, the impact of warming temperature on crop phenology and cropping systems is one of hot topics in studies of agricultural geography.

Warming temperature potentially gives a chance of crop yield increase in regions where cultivated land is scare (e.g., the Loess Plateau [LP] of China). As we know, the "Grain for Green" project of the LP of China is the largest ecological restoration project ever implemented in a developing country (Feng *et al*., 2016; Jia *et al*., 2017a). The project effectively reduced the area of slope cropland and the magnitude of regional soil erosion (Wang *et al*., 2015; Feng *et al*., 2016; Ouyang *et al*., 2016; Jia *et al*., 2017b). Note that decrease of cultivated land is bound to reduce the crop yield (Liu *et al*., 2017a). To deal with the conflicts between human and food security, Yan'an city of the LP is the first to practice the project of land consolidation (Liu, 2015; Liu *et al*., 2017a). However, compared to the decreased area of cultivated land, the newly increased area of cultivated land is far insufficient. The satellite-based statistics showed that in the past 15 years, the net decrease of cultivated land was ~$1 \times 10^4$ km$^2$ across entire LP (Liu *et al*., 2014). There is however ~108 million people living in this region (Feng *et al*., 2016). How to defend the conflicts between human and cultivated land is thus a large challenge. Regionally, an effective way could allow limited cultivated land to produce more crop yield. The traditional cropping systems of LP is one crop per year (Sun *et al*., 2018). Spring maize is the staple grain crop in most LP. However, the simple agricultural productive structure only helps farmers gain the limited food and economic benefits. Agricultural productive structure and layout play important roles in increasing total crop yield and farmers' income. In the context of climate change, whether the traditional cropping systems have the potential to be replaced by cropping systems with two crops per year or three crops in 2 years is rarely reported. Thus, more studies and practices are needed to assess possible effects of climate change on agro-ecological conditions and cropping systems.

To take fully advantage of newly increased consolidated land and uncover the new mode of cropping systems, our research group set up a field station in Yangjuangou watershed of Yan'an city in 2014 (Liu *et al*., 2017a). Area of the Yangjuangou watershed is approximate 2 km$^2$ with averaged elevation of ~1,140 m. It is worth noting that the watershed is a typical watershed in the LP, and it is one of newly increased consolidated lands of the LP through land consolidation engineering (Liu *et al*., 2017a). In 2016–2017, our research group succeeded in the new mode of maize and forage rape rotation in the context of temperature increase, suggesting the feasibility of replacing one crop per year with two crops per year in Yangjuangou watershed (Liu *et al*., 2017a). Although replacing one crop per year with two crops per year in the field experiment is successful, whether the new mode is suitable for larger area in the LP is still unknown.

Thermal conditions play an important role regulating the cropping systems, the crop growth and the agricultural products. Generally, crops need accumulate a certain quantity of heat to satisfy the requirements of crop growth (Dong *et al*., 2009; Gao and Liu, 2011; Liu *et al*., 2013; Hou *et al*., 2014; Xu and Li, 2016). The 10 °C is the start temperature of suitable growth of thermophilic crop (Dai *et al*., 2015). The annual accumulated temperature ≥10 °C (AAT10) is thus regarded as a key indicator of thermal resource in the agro-ecological system. AAT10 largely affects the choice of crop varieties, crop phenology, cropping systems and crop patterns. Some previous studies improved our knowledge on the impacts of AAT10 change (Li *et al*., 2013; Liu *et al*., 2013; Dai *et al*., 2015; Meng *et al*., 2016). For example, Dai *et al*. (2015) analysed the change of AAT10 in southern China during 1960–2011 and stated that the increased AAT10 was conducive to extend the planting boundaries to high latitude and high altitude. The study of Liu *et al*. (2013) reported that AAT10 increased 9–116 °C·day/10a during 1961–2007, leading to a northwards expansion of the northern limits of maize. Based on daily air temperature during 1960–2014, Meng *et al*. (2016) reported that a new central subtropical zone obviously was observed. Their study indicated that the area of north subtropical zone and warm temperature zone gradually extended, and the area of middle temperature zone and cold temperature zone gradually narrowed in Shanxi–Shaanxi–Inner Mongolia region. In northern China, AAT10 of 3,400 °C·day is an important criterion, which divides the boundary of cropping systems with one crop per year (mid-temperate zone with AAT10 ranging 1,600–3,400 °C·day) and cropping systems with two crops per year or three crops in 2 years (warm temperate zone with AAT10 ranging 3,400–4,500 °C·day). Thus, clarifying changes of boundary with 3,400 °C·day is very important for regionalization of cropping systems across the LP, because it can map the potential regions where is feasible for the cropping systems with two crops per year or three crops in 2 years. However, the change of AAT10 and its effect on regional agriculture development in the LP are rarely reported.

Therefore, the aims of this study are (a) to investigate the spatial patterns and trends of AAT10 in entire LP in the past 55 years, (b) to map the extended area of warm temperate zones and (c) to uncover the possible reasons of AAT10 change and AAT10 change for the potential implication of regional agriculture development.

## 2 | DATA AND METHODS

### 2.1 | Study area

The LP is one of Chinese four Plateaus, covering the area of ~$62.4 \times 10^4$ km$^2$ (Figure 1). The region is mainly dominated by a semi-arid continental monsoon climate with annual mean precipitation decreasing from ~700 mm in the southeast to ~50 mm in the northwest and annual mean air temperature ranging 0–13 °C. In recent decades, a warming trend is dominating this region (Wang *et al*., 2015; Feng

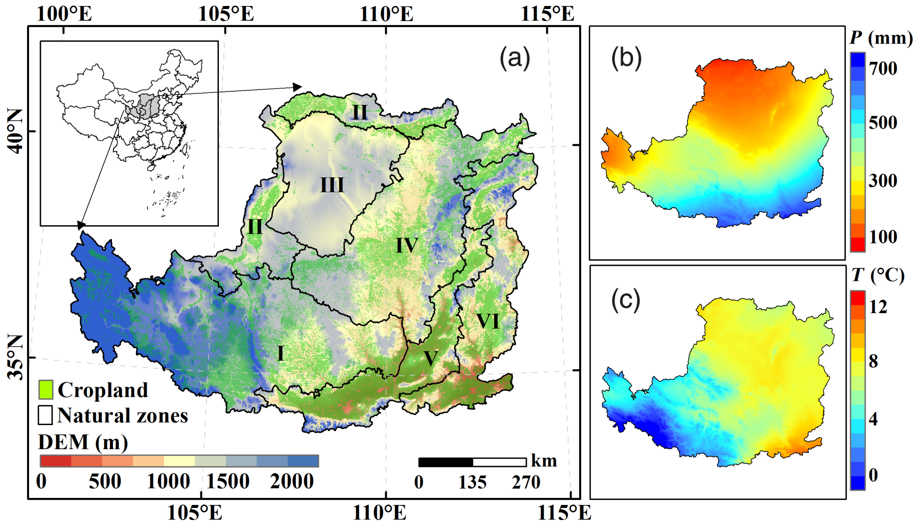


**FIGURE 1** (a) Location of the LP, as well as its DEM and distribution of cropland in 2010. The LP covers six natural zones, including (I) Loess Gully region, (II) irrigation region, (III) sand and desert region, (IV) loess hilly and gully region, (V) valley plain region and (VI) earth-rock mountain region. (b) Spatial annual mean precipitation (*P*). (c) Annual mean temperature (*T*) [Colour figure can be viewed at wileyonlinelibrary.com]

*et al*., 2016). Area of satellite-based cropland accounts for ~30% of entire LP in 2010 (Liu *et al*., 2014).

## 2.2 | Data and processing

The gridded daily air temperature and precipitation data with the resolution of 0.25° longitude by 0.25° latitude for the period of 1961–2015 were collected from CMA. The gridded data were developed from the records of 2,416 meteorological stations (termed as CN05.1) (Wu and Gao, 2013). Thin-plate smoothing splines (ANUSPLIN) method as well as digital elevation model (DEM) as the covariate was used for the gridded interpolation (Hutchinson *et al*., 2009; Liu *et al*., 2018). The detailed steps of interpolation can be found in the previous studies (Xu *et al*., 2009; Wu and Gao, 2013). Compared to the freely shared 751 basic meteorological stations, the number of the observed stations of CN05.1 data is largely increased. Thus, CN05.1 data had theoretically stronger performances due to employing more available meteorological stations. The data of the LP used in this study were extracted from the CN05.1.

Other auxiliary data used in this study included 1 km land use data in 2010 collecting from Centre for Resource and Environment Science Data, Chinese Academy of Sciences (Liu *et al*., 2014), 1 km NASA Shuttle Radar Topography Mission (SRTM) DEM and the Moderate-resolution Imaging Spectroradiometer (MODIS) Land Surface Temperature (LST). The 1-km spatial resolution and 8-day temporal interval LST data for the period of 2001–2015 were collected from Land Processes Distributed Active Archive Center (LPDAAC). LST data include daytime and night-time temperature observations. This study first used Savitzky–Golay filter to smooth LST data by combining with quality control files (Wang *et al*., 2017). Subsequently, we used smoothed daytime and night-time temperature to calculate mean LST at each 8-day interval, and used each 8-day LST and the 6 degree polynomial model to derive daily LST. Finally, based on the relationship between LST and station-based interpolated air temperature at the daily scale, we derived LST-based air temperature. The data were further used to validate our findings in this study.

Observed meteorological data of Yangjuangou watershed are only available since 2016. Therefore, to explain the potential mechanism of the successful field experiment with replacing one crop per year with two crops per year, long-term meteorological data (1951–2017) in Yan'an meteorological station were used as the best substitute of Yangjuangou meteorological observation (see section 4.2). Two reasons were mainly considered: (a) Yan'an meteorological station is the nearest station around Yangjuangou watershed and (b) daily temperature variations are in agreement with those of Yangjuangou watershed (Figure S1, Supporting Information). Yan'an meteorological data were collected from National Meteorological Administration of China (CMA). To minimum the impact of urban expansion on meteorological observations, Yan'an meteorological station was relocated in 2013. Thus, to eliminate the impact of relocation of meteorological station on air temperature, we corrected the data in 1951–2012 using the elevation information of new (1180.5 m) and old stations (958.5 m). This work ensures the homogeneity of observed air temperature data during the period of 1951–2017 (Liu *et al*., 2018).

## 2.3 | Statistic analyses

AAT10 is the sum of daily mean air temperature being steadily equal or greater than 10 °C, which is the minimum biology temperature. The 5-day simple moving average method was used to extract the dates of being steadily equal or greater than 10 °C (Dong *et al.*, 2009; Liu *et al.*, 2013). AAT10 was computed using the following formula:

$$\mathrm{AAT10} = \sum_{i=a}^{n} \overline{T_i}, \overline{T_i} \geq 10^{\circ}\mathrm{C}, \tag{1}$$

where $\overline{T_i}$ is the average temperature on day of year (DOY) $i$th, $a$ and $n$ are the start date of $\overline{T} \geq 10$ °C (SDT10) and end date of $\overline{T} \geq 10$ °C (EDT10), respectively. It is important to note that if $\overline{T}$ is lower than 10 °C, $\overline{T} = 0$ in the above formula. The range between SDT10 and EDT10 is termed as length of durations of $\overline{T} \geq 10$ °C (LDT10).

To analyse the impacts of warming temperature on SDT10, EDT10, LDT10 and AAT10, the entire periods of 1961–2015 was divided into five different periods, covering 1960s (1961–1969), 1970s (1970–1979), 1980s (1980–1989), 1990s (1990–1999) and 2000–2015. The spatial patterns of each variable (SDT10, EDT10, LDT10 and AAT10) were first investigated in five different periods, respectively. Then, this study used the regression coefficient of linear regression to spatially assess the trend of each variable (Wang *et al.*, 2017). The regression coefficient (slope) was calculated as follows:

$$\mathrm{Slope} = \frac{n\sum X_i Y_i - \sum X_i \sum Y_i}{n\sum X_i^2 - \left(\sum X_i\right)^2}, \tag{2}$$

where $X_i$ is the $i$th year, $Y_i$ is the corresponding variable (SDT10, EDT10, LDT10 or AAT10) in the $i$th year and $n$ is the sum of number of years. Student's $t$-test was used to investigate the statistical significance of trends at the 0.05 or 0.01 level ($p < 0.05$ or $p < 0.01$).

AAT10 plays an important role in agricultural climatic regionalization and physical geographic regionalization (Dong *et al.*, 2009; Dai *et al.*, 2015). In this study, the classical criteria from traditional regionalization were used to investigate changes of accumulate temperature zones (Table 1) in the LP.

To clearly describe the impact of changes of daily air temperature on AAT10, a 6 degree polynomial was employed to simulate the change of daily air temperature during 1960s and during 2000–2015 (Piao *et al.*, 2006; Liu *et al.*, 2017b). The determination coefficient ($R^2$) was used to evaluate the accuracy of simulations (Liu *et al.*, 2017c). Bias was further used to detect the data difference in two periods. Mann–Kendall nonparametric statistical method (please see Appendix section) was used to investigate the trend and abrupt tests of AAT10 (Mann, 1945; Goossens and Berger, 1986; Fu and Wang, 1992).

## 3 | RESULTS

### 3.1 | Spatial patterns of SDT10, EDT10, LDT10 and AAT10

The spatial distributions of SDT10 (Figure S2), EDT10 (Figure S3), LDT10 (Figure S4) and AAT10 (Figure 2) showed elevation-dependent distribution. Lower elevation regions had earlier SDT10, later EDT10, longer LDT10 and higher AAT10 as showed in southeastern LP. In contrast, western LP with higher elevation gave later SDT10, earlier EDT10, shorter LDT10 and less AAT10.

In the past 55 years, regions with earlier SDT10 were gradually extending. For example, across the LP, regions with SDT10 being DOY100-110 changed from 61.4% (1960s) to 45.1% (1970s), then to 37.9% (1980s) and 30.2% (1990s), finally to 10.5% of 2000–2015. Accordingly, regions with SDT10 being DOY90–100 were gradually increasing. In 1960s, 20.9% of the entire LP only located in the range of DOY90-100. However, regions with SDT10 being DOY90-100 increased to 44.2% in 2000–2015. Besides, in 2000–2015, regions with SDT10 being DOY ≤ 90 increased by ~30% relative to those in the period of 1961–1999 (~10%).

During the period of 1961–2015, the large-area delays mainly focused on the regions with EDT10 ranging from DOY280-290 to DOY290-300. Regions with EDT10 being DOY280-290 were decreasing from 56.9% in 1960s to 38.0% in 2000–2015 across the LP. However, regions with EDT10 being DOY290-300 increased by 24.3% in 2000–2015 compared to that in 1960s (15.9%).

LDT10 of most regions got longer from 1960s to 2000–2015 due to earlier SDT10 and later EDT10. The main changes located in these regions with LDT10 ranges of DOY170-190 and DOY190-210. Regions with LDT10 being DOY170-190 decreased from 56.5% in 1960s to 16% in 2000–2015 across the LP. In contrast, regions with LDT10 being DOY170-190 gradually increased from 20.8% of entire study area in 1960s to 55.5% in 2000–2015. These regions concentrated on middle and northern LP (Figure S3e).

Most LP showed earlier SDT10, later EDT10 and longer LDT10. Naturally, most regions thus had higher

**TABLE 1** Criteria of AAT10-based accumulate temperature zones and corresponding cropping systems

| Accumulate temperature zones | AAT10 (°C·day) | Cropping systems | Crop varieties |
|---|---|---|---|
| Cold temperate zone | **<1,600** | One crop per year | Spring wheat, barley and potato |
| Mid-temperate zone | **1,600–3,400** | One crop per year | Spring wheat, soybean, maize, millet and sorghum |
| Warm temperate zone | **3,400–4,500** | Two crops per year or three crops in 2 years | Winter wheat, maize, millet and sweet potato |
| Subtropical zone | **4,500–8,000** | Two or three crops per year | Winter wheat and rice |
| Tropical zone | **>8,000** | Three crops per year | Rice, sugarcane and rubber |

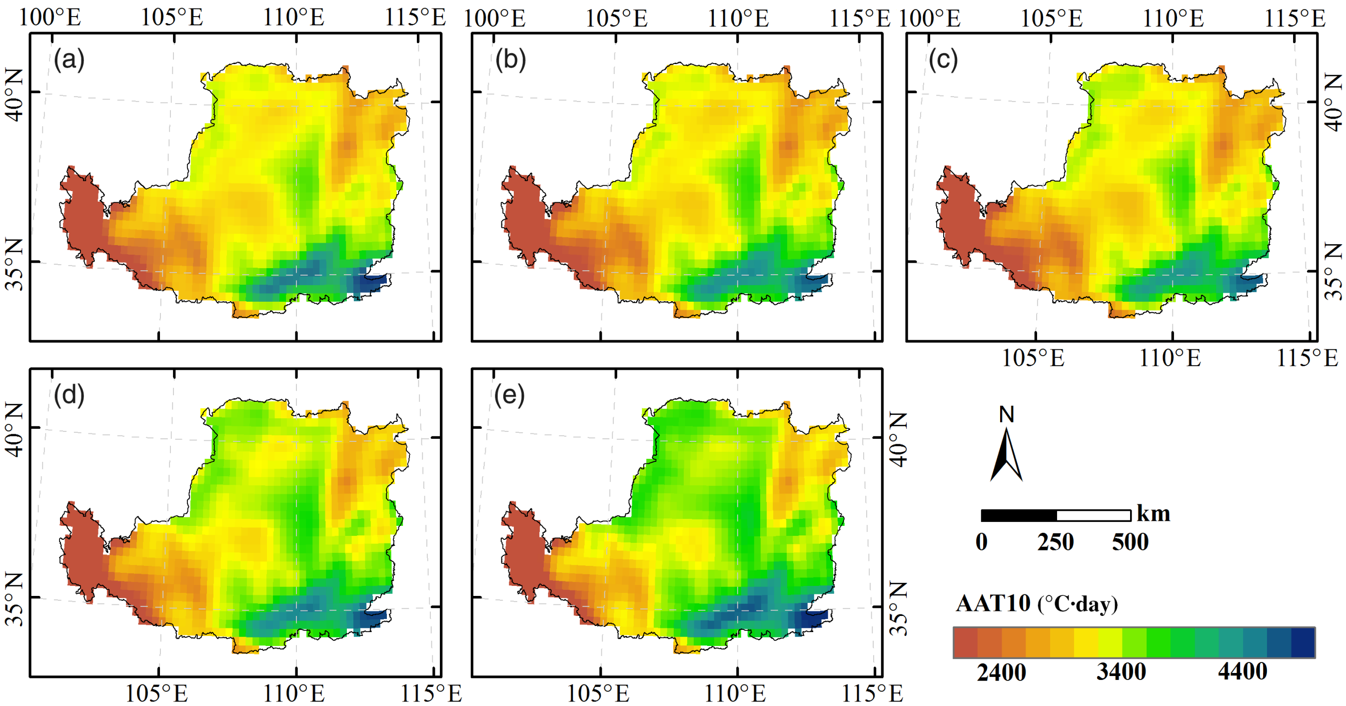


**FIGURE 2** Spatial patterns of annual accumulated temperature with ≥10 °C. (a) 1960s, (b) 1970s, (c) 1980s, (d) 1990s and (e) 2000–2015 [Colour figure can be viewed at wileyonlinelibrary.com]

AAT10 during the past 55 years. Large changes focused on these regions with AAT10 being 2,500–3,400 and 3,400–4,000 °C·day. Regions with AAT10 being 2,500–3,400 °C·day decreased from 62.0% of entire study area in 1960s to 32.1% in 2000–2015. Regions with AAT10 being 3,400–4,000 °C·day however increased from 19.8% of entire study area in 1960s to 49.3% in 2000–2015, and mainly located in middle and northern regions of the LP (Figure 2e).

## 3.2 | Trends of spatial SDT10, EDT10, LDT10 and AAT10

Compared to the spatial patterns, the temporal trends in SDT10, EDT10, LDT10 and AAT10 may play more important roles in quantifying the changes of these metrics in response to climate change. In the past 55 years, significantly advanced SDT10, prolonged EDT10 and increased AAT10 were observed in most LP ($p < 0.05$).

Figure 3a showed that 81.9% SDT10 of entire LP presented advanced trends with 1–3 days. Also, advanced SDT10 of these regions were all significant ($p < 0.05$, Figure 3b). Besides, there were 16.1% SDT10 performing non-significantly advanced or delayed trends ($p > 0.05$). As Figure 3c,d showed, 93.2% EDT10 of entire LP with 0–2 days of delayed trends were observed, but most delayed EDT10 were no significance ($p > 0.05$). Regions with EDT10 being significantly delayed were only 36.8%, mainly locating in the mid-western LP. In the context of the interactions of advanced SDT10 and delayed EDT10, 89.2% LDT10 of entire LP showed significantly increased trends with 2–5 days ($p < 0.05$). Western LP had higher increased trends than eastern LP. There were only 8.8% LDT10 performing non-significantly increased trends, mainly locating in southern and eastern LP (Figure 3f). In Figure 3g, 99.9% AAT10 showed significantly increased trends ($p < 0.05$), of which increased trends of AAT10 ranging from 40 to 100 °C·day/10a accounted for 92.1% of entire LP. Spatially, increased trends of AAT10 gradually increased from southeast to northern LP.

Also, abrupt tests of AAT10 in entire LP and six natural zones were investigated, respectively (Figure S5). For entire LP, a significantly increased trend was observed with 65.1 °C·day/10a ($p < 0.01$) in the past 55 years. AAT10 showed a decreased trend before 1997, however after 1997 an increased trend was observed. The increased trend was significant at the 0.05 statistical level after 2003. The abrupt test indicated that the mutation point was located in 1997. The averaged AAT10 before 1997 and after 1997 were 3,037 and 3,306 °C·day. Similarly, AAT10 of six natural zones also suggested significantly increased trends ($p < 0.01$), respectively. However, years of the mutation point were different in six natural zones. Three zones of northern LP, including (II) irrigation region, (III) sand and desert region and (IV) Loess Hilly and Gully region, had mutation points in 1996, 1995 and 1996, respectively. Among them, (II) irrigation region and (III) sand and desert region had much stronger increased trends with 90.2 and 84.3 °C·day/10a in the past 55 year ($p < 0.01$). Three zones located in southern LP, covering (I) Loess Gully region, (V) valley plain region and (VI) earth-rock mountain region, showed mutation points

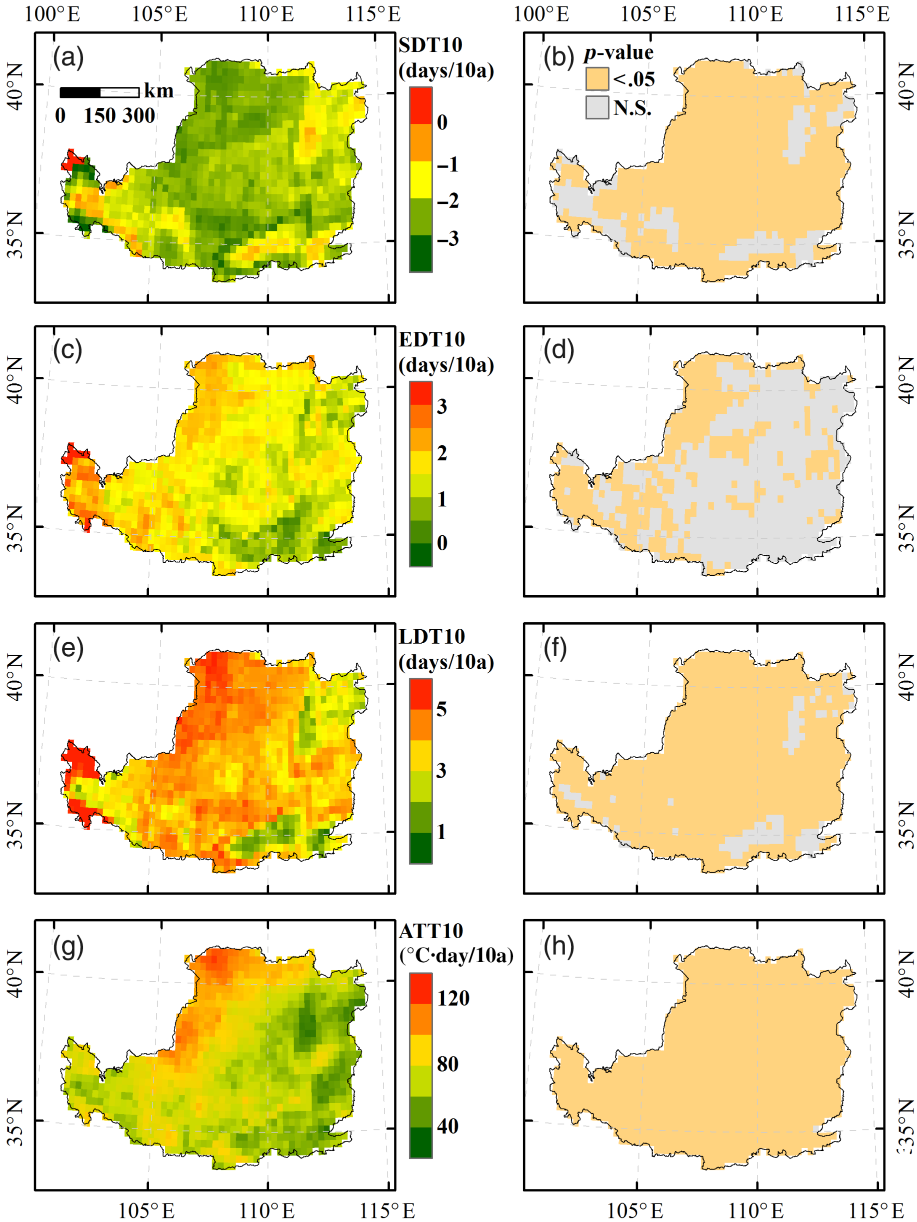


**FIGURE 3** Spatial trends of SDT10 (a), EDT10 (c), LDT10 (e) and AAT10 (g) and their corresponding significance at the 0.05 significance level (b,d,f,h). N.S. represents no significance difference at the 0.05 significant level [Colour figure can be viewed at wileyonlinelibrary.com]

in 2000, 2001 and 2001, respectively. A weaker increased trend was observed in (VI) earth-rock mountain region with 46.9 °C·day/10a ($p < 0.01$).

### 3.3 | Changes of accumulated temperature zones related to cropping systems

The spatial distributions of accumulated temperature zones (especially regions with AAT10 ≥ 3,400 °C·day changed from one AAT10 scale to another) were identified according to the criteria of AAT10-based accumulate temperature zones (Table 1). Figure 4 showed that in the past 55 years, regions with AAT10 ≥ 3,400 °C·day gradually extended from 21.0% (1960s) to 34.2% (1990s), then to 50.3% (2000–2015) of entire LP. In 1961–1979, regions with AAT10 ≥ 3,400 °C·day mainly focused on the southeastern LP. During the two decades, the area of regions with AAT10 ≥ 3,400 °C·day had only a little change. In 1980s, the southeastern LP had similar regions as well as those of 1960s and 1970s. However, regions with AAT10 ≥ 3,400 °C·day were observed in the northwestern LP, although the area of regions was only ~1% of entire LP. In 1990s, two regions with AAT10 ≥ 3,400 °C·day in the southeastern and northwestern LP were further extended. Particularly, northwestern LP had 6.3% regions with AAT10 ≥ 3,400 °C·day. During 2000–2015, regions with AAT10 ≥ 3,400 °C·day in the southeastern and northwestern LP became a larger unit as the grey regions of Figure 4 showed. These results implicated that most LP had a large potential to transfer its traditional cropping systems (one crop per year) to new cropping systems (e.g., two crops per year or three crops in 2 years) in the context of climate change. To further test the reliability of our

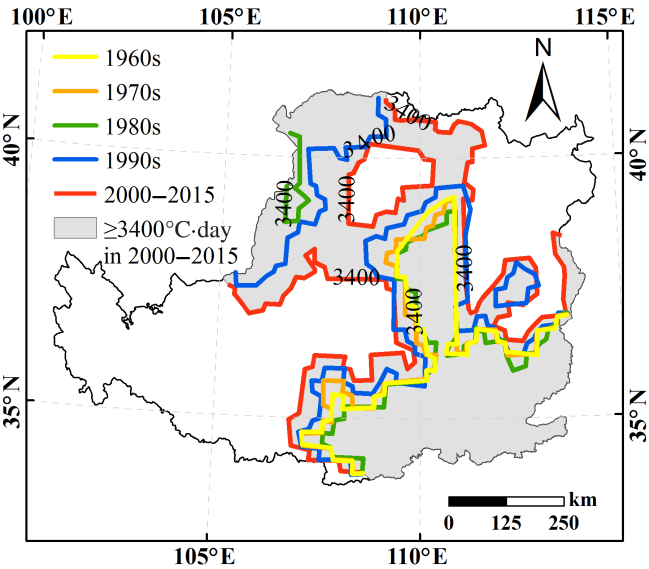


**FIGURE 4** Lines of 3,400 °C·day (AAT10) in 1960s (yellow line), 1970s (orange line), 1980s (green line), 1990s (blue line) and 2000–2015 (red line). The grey area represents regions with AAT10 ≥ 3,400 °C·day in 2000–2015 [Colour figure can be viewed at wileyonlinelibrary.com]

findings shown in Figure 4, this study also conducted the similar analyses based on satellite-based temperature data (Figure S6). The analyses performed a similar spatial pattern shown in Figure 4, suggesting the robustness of our results.

## 4 | DISCUSSION

### 4.1 | Gridded temperature data and changes of AAT10

CN05.1 is a new version data sets, which employed ANUSPLIN method and more abundant meteorological stations to derive the spatial products. Theoretically, the data sets should have a more robust performance (Wu and Gao, 2013). Some studies thus use CN05.1 data sets to answer their concerned questions (Wen *et al.*, 2013; Zhou *et al.*, 2016). This study directly used CN05.1 spatial data to clarify the spatial patterns and temporal trends of SDT10, EDT10, LDT10 and AAT10. Traditionally, previous studies first computed SDT10, EDT10, LDT10 and AAT10 using station-based data, then interpolated station-based results to the spatial scale. It is worth noting that there is a debate for which methods are more appropriate. Many studies potentially suggest that it would be more appropriate to grid the data first and then to compare them (Zhao and Fu, 2006; Ma *et al.*, 2008). An important reason is likely that climatic variables directly changing along with elevation have more explicit physical meaning, and much easier to make sense.

In interpolation, some studies generally used Kriging or inverse-distance weighting methods without considering the effect of DEM. These traditional interpolate methods often perform well over regions with lower elevation or relatively covered by dense stations (Yuan *et al.*, 2014; Yue *et al.*, 2016; Cui *et al.*, 2018; Qu *et al.*, 2018). However, in complex terrain, many studies have reported that AUNSPIN method shows a stronger performance due to considering the impacts of DEM on climatic variables (Hutchinson *et al.*, 2009; Liu *et al.*, 2018).

This study offers a more detailed discussion on AAT10 in the LP. In the context of climate change, warming temperature makes SDT10 advanced and EDT10 delayed, further increases LDT10 and AAT10. Many previous studies have reported the advanced and delayed effects of climate change on SDT10 (or spring temperature) and EDT10 (or autumn temperature) (Xoplaki *et al.*, 2005; Abatzoglou and Redmond, 2007; Dai *et al.*, 2015; Wang *et al.*, 2017). These reports are consistent with our findings. However, our study suggests that advanced SDT10 contributes more to LDT10 increase compared with delayed LDT10 does. SDT10 better explained the variations of LDT10 ($R^2$ = 0.76, $p < 0.01$) relative to EDT10 ($R^2$ = 0.46, $p < 0.01$). The Pearson corrections show that the relationships between AAT10 and SDT10 ($R^2$ = 0.64, $p < 0.01$) are much stronger than those between AAT10 and EDT10 ($R^2$ = 0.32, $p < 0.01$). It potentially suggests the large contribution of SDT10 to AAT10 increases. Compared with single SDT10 or EDT10, the combined effect of the above two, namely LDT10, showed the best correlations with AAT10 ($R^2$ = 0.78, $p < 0.01$).

Besides, except for advanced SDT10, delayed EDT10 and increased LDT10, warming temperature during the period of LDT10 is also responsible for AAT10 increase. To clearly describe this question, Figure 5 shows the change of estimated daily air temperature during 1960s and during 2000–2015. The accuracy of simulations are significantly 0.993 ($R^2$) for 1960s and 0.996 ($R^2$) for 2000–2015, respectively. This study finds that annual air temperature in 2000–2015 is 1.1 °C higher than that in 1960s. Warming magnitude of winter temperature is the largest with the difference of 1.7 °C, followed by spring temperature (bias = 1.4 °C), autumn temperature (bias = 0.9 °C)

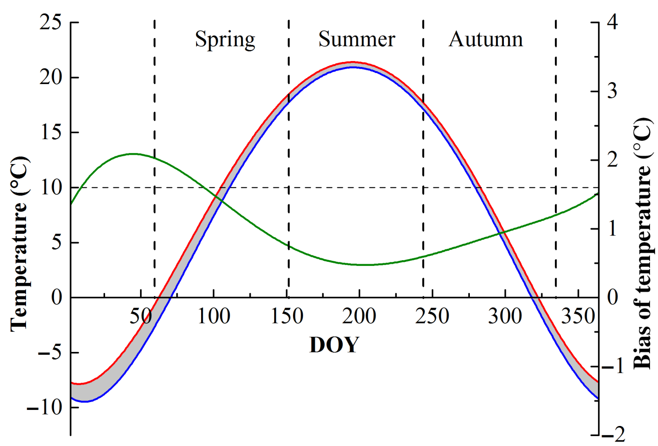


**FIGURE 5** Estimated annual variations of 1960s (blue sloid line) and 2000–2015 (red solid line). The grey area represents the increased temperature in 2000–2015 relative to 1960s. The green sloid line is the bias of temperature during 1960s and during 2000–2015 [Colour figure can be viewed at wileyonlinelibrary.com]

and summer temperature (bias = 0.6 °C). The annual air temperature ≥10 °C in 2000–2015 are however 0.7 °C higher than that in 1960s. Air temperature ≥10 °C in spring, summer and autumn are 1.1, 0.6 and 0.7 °C, respectively. Spring temperature contributes more to AAT10 increase relative to autumn and summer temperature.

### 4.2 | Potential implication for regional agriculture development

To develop a deeper understanding of the potential of cropping system change, this study used a long-term (1951–2017) observation of daily air temperature from Yan'an meteorological station (see section 2.2) and our 2-year field experiment (2016–2017) in Yangjuangou watershed of Yan'an city, respectively. Air temperature in Yan'an meteorological station is a proxy of Yangjuangou meteorological observation (Figure S1; see section 2.2). This study showed the trends of annual temperature and AAT10 (Figure 6). In 1951–2017, annual temperature performed an increased trend with 0.4 °C/decade ($p < 0.01$). Specifically, averaged annual temperature after the year of 2000 increased by ~2.0 °C compared to that before the year of 1970. The strongest change was observed in 1990s. Warming temperature resulted in AAT10 increase. AAT10 increased from 3,162 °C·day in 1950s and 1960s to 3,667 °C·day after 2000. Note that AAT10 steadily exceeded 3,400 °C·day (the lower limit of the cropping systems of two crops per year) since the year of 1997. Besides, other evidence, for example, advanced crop phenological metrics and shrinkable phenological periods, also supported the possibility of replacing one crop per year with two crops per year in LP (He *et al.*, 2015). Based on some findings of warming temperature and phenological metrics, we have conducted a field experiment of replacing one crop per year with two crops per year in Yangjuangou watershed of Yan'an city since 2016. The field experiment suggested that AAT10 with 2,100 °C·day could meet the heat requirement of spring maize growth. Also, the observed data from forage rape growth after maize harvesting supported the new mode of spring maize and forage rape rotation in Yangjuangou watershed (Liu *et al.*, 2017a).

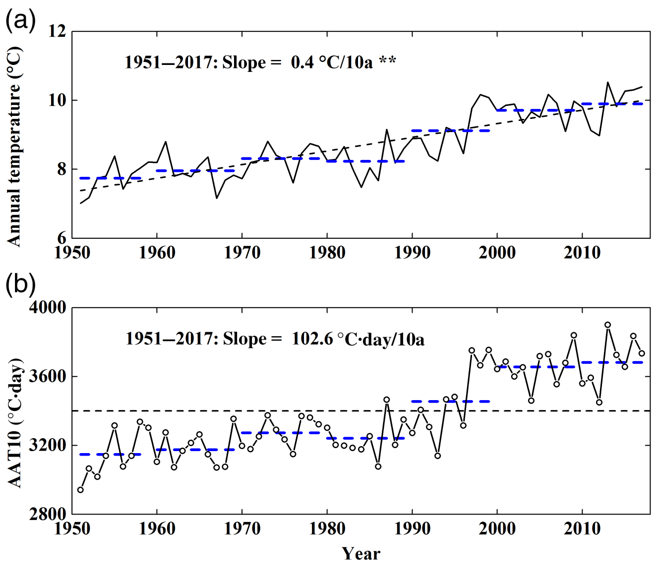


**FIGURE 6** Trends of annual temperature (a) and AAT10 (b) in Yan'an meteorological station (a proxy of Yangjuangou meteorological observation). The symbols ** represent the significance at the 0.01 level. The blue dashed lines represent the average of each decade. In (a), the black dashed line represents the trend of annual temperature during 1951–2017. In (b), the black dashed line represents 3,400 °C·day of AAT10 [Colour figure can be viewed at wileyonlinelibrary.com]

The impacts of climate change on the traditional cropping system are widely reported, including the positive and negation impacts. For example, some studies have stated that climate change is positively accelerating the crop developments, hastening the crop maturations and leading to reductions in the length of the growing season, but also climate change can result in negative impacts on the crop yield if there are no countermeasures (Olesen and Bindi, 2002; Liu *et al.*, 2013). To defend the negative impacts of climate change and increase crop yield in a longer growing season, there are studies indicating that planting new varieties or taking new cropping systems could be effective management measurements (Dong *et al.*, 2009; Liu *et al.*, 2013). The study of northeast China implicated that crop yield would increase by 7–10% after traditional varieties were replaced by new varieties. Some similar results were also reported by previous studies of other regions (Wang *et al.*, 1992; Torriani *et al.*, 2007). These potentially suggest that we should use well the advantages of AAT10 increase and advanced STD10 to uncover the new mode of regional agriculture, especially in using limited cultivated land to increase the crop yield, for example, the LP. It could be an effective countermeasure for regional sustainability and food security.

Traditionally, the cropping system is one crop per year in most LP (Sun *et al.*, 2018). Our findings as well as recent 2-year field-based experiment imply that most LP had a large potential to develop new cropping systems with replacing one crop per year with two crops per year given increase of spatially explicit AAT10. The new cropping systems could help alleviate the conflict of human and food security in the LP. On the other hand, after the "Grain for Green" project has been practiced since the year of 1999, a series of related polices, such as forest and grassland conservation, and bans on grazing, are also launched. These polices obligate the traditional operations of animal feeding (e.g., grazing) to shift to captivity. The planting of forage rape can potentially help alleviate the conflict of the livestock and herbage allowance in this region (Liu *et al.*, 2017a).

### 4.3 | Analyses of restrictive factors

Increase of AAT10 provides a large potential to develop new cropping systems in most LP, but the importance of soil conditions, water resources and reasonable cropland managements is not to be neglected for ensuring the success of replacing one crop per year with two crops per year. In recent years, some useful efforts have been conducted in the improvement of soil conditions (Han *et al*., 2012; Li *et al*., 2017). For example, Han *et al*. (2012) reported that proportionately remixing the red clay and sandy soil can effectively improve physical characteristics of local soil of Mu Us Sandy Land of China, and further achieve the goal of water and soil resources effective utilization. The applications of these engineering measures will be helpful for regional cropping system change in regions with poor soil conditions. On the other hand, regional water resources are also an important restrictive indictor. The study observes that regions with AAT10 ≥ 3,400 °C·day walk across precipitation belts ranging from 200 to 800 mm (Figure 7a). In southeastern land consolidation regions with AAT10 ≥ 3,400 °C·day, precipitations with more than 500 mm and abundant river net have a great potential to meet the water resource requirements of regional cropping system change. Note that annual precipitation in middle LP shows significantly increased trends

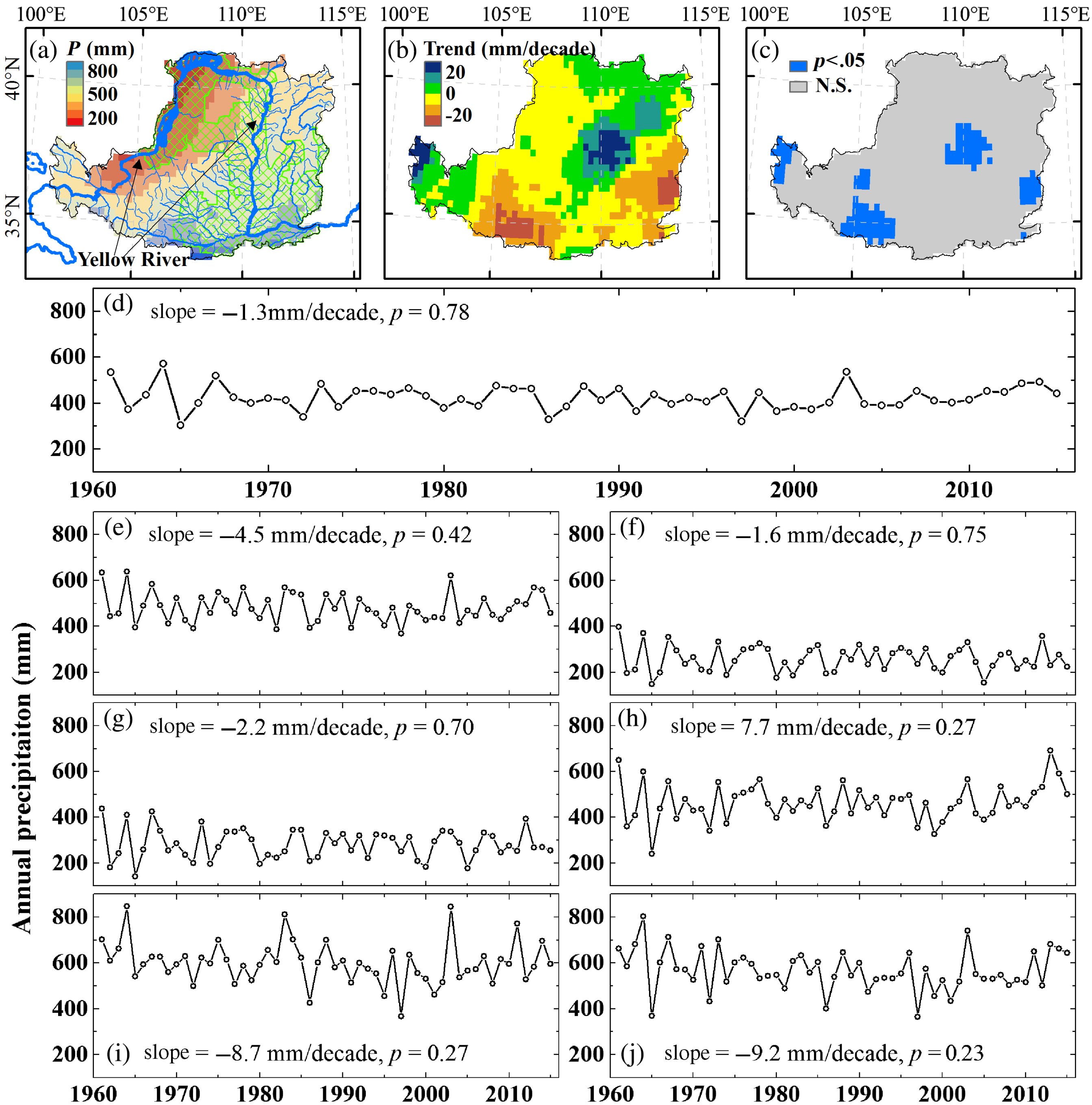


**FIGURE 7** Spatial distribution (a) and trend (b) of annual precipitation ($P$, a) for the period of 1961–2015 and its corresponding spatial significance (c). Subfigures (d)–(j) show the inter-annual changes of entire LP, (I) Loess Gully region, (II) irrigation region, (III) sand and desert region, (IV) Loess Hilly and Gully region, (V) valley plain region and (VI) earth-rock mountain region for the period of 1961–2015, respectively. N.S. represents no significance ($p$ > 0.05) [Colour figure can be viewed at wileyonlinelibrary.com]

($p < 0.05$, Figure 7b,c). It may cause a beneficial effect for regional agricultural development. Although northwestern land consolidation regions with AAT10 ≥ 3,400 °C·day are located in precipitation belts with 200–400 mm, abundant water resources of the Yellow River are likely helpful for regional cropping system change, especially in regions around the Yellow River. Besides, reasonable cropland managements also play an important role in regional cropping system change. For example, early spring film mulching can regulate the partitioning of net radiation into latent heat and sensible heat in surface soil and then maintain a more constant soil temperature. Also, early spring film mulching can also increase soil moisture, which is very important for crop growth (Meng *et al*., 2015).

## 5 | CONCLUSIONS

In this study, on basis of the practice of 2-year field experiment in Yangjuangou watershed of the LP, a long-term (1961–2015) and high-resolution (0.25° longitude by 0.25° latitude) daily gridded air temperature was used to clarify spatiotemporal changes of annual accumulated temperature ≥10 °C (AAT10) and its potential implication for regional agriculture development over entire LP. Results indicated that significantly extended length of durations of 5-day moving average temperature ($\overline{T}$) ≥10 °C (LDT10), as well as warming temperature, is responsible for increased AAT10 of the LP. Increased AAT10 has largely extended the area of warm temperate zone since 1990s. Area of warm temperate zone increased by ~29% of entire LP in the past 55 years. These findings suggest that most LP, especially in regions with good soil conditions and sufficient water resources, had a large potential to transfer its traditional cropping systems (one crop per year) to new cropping systems (e.g., two crops per year) in the context of climate change.

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### REFERENCES

Abatzoglou, J.T. and Redmond, K.T. (2007) Asymmetry between trends in spring and autumn temperature and circulation regimes over western North America. *Geophysical Research Letters*, 34(18), L18808.

Abbas, G., Ahmad, S., Ahmad, A., Nasim, W., Fatima, Z., Hussain, S., Rehman, M.H.U., Khan, M.A., Hasanuzzaman, M., Fahad, S., Boote, K.J. and Hoogenboom, G. (2017) Quantification of the impacts of climate change and crop management on phenology of maize-based cropping system in Punjab, Pakistan. *Agriculture and Forest Meteorology*, 247, 42–55.

Cui, L., Wang, L., Singh, R.P., Lai, Z., Jiang, L. and Yao, R. (2018) Association analysis between spatiotemporal variation of vegetation greenness and precipitation/temperature in the Yangtze River basin (China). *Environmental Science and Pollution Research*, 25, 21867–21878.

Dai, S., Hailiang, L.I., Luo, H., Zhao, Y. and Zhang, K. (2015) Changes of annual accumulated temperature over southern China during 1960–2011. *Journal of Geographical Sciences*, 25(10), 1155–1172.

Ding, Y., Ren, G., Zhao, Z., Xu, Y., Luo, Y., Li, Q. and Zhang, J. (2007) Detection, causes and projection of climate change over China: an overview of recent progress. *Advances in Atmospheric Sciences*, 24(6), 954–971.

Dong, J., Liu, J., Tao, F., Xu, X. and Wang, J. (2009) Spatio-temporal changes in annual accumulated temperature in China and the effects on cropping systems, 1980s to 2000. *Climate Research*, 40(1), 37–48.

Feng, X., Fu, B., Piao, S., Wang, S., Ciais, P., Zeng, Z., Lü, Y., Zeng, Y., Li, Y., Jiang, X. and Wu, B. (2016) Revegetation in China's Loess Plateau is approaching sustainable water resource limits. *Nature Climate Change*, 6, 1019–1022.

Fu, C. and Wang, Q. (1992) The definition and detection of the abrupt climatic change. *Chinese Journal of Atmospheric Sciences*, 16(4), 482–493 (in Chinese).

Gao, J. and Liu, Y. (2011) Climate warming and land use change in Heilongjiang Province, northeast China. *Applied Geography*, 31(2), 476–482.

Goossens, C.H. and Berger, A. (1986) Annual and seasonal climatic variations over the Northern Hemisphere and Europe during the last century. *Annale Geophysicae*, 4(4), 385–400.

Han, J., Liu, Y. and Luo, L. (2012) Research on the core technology of remixing soil by soft rock and sand in the Maowusu sand land region. *China Land Science*, 26(8), 87–94 (in Chinese).

He, L., Asseng, S., Zhao, G., Wu, D., Yang, X., Zhuang, W., Jin, N. and Yu, Q. (2015) Impacts of recent climate warming, cultivar changes, and crop management on winter wheat phenology across the Loess Plateau of China. *Agriculture and Forest Meteorology*, 200, 135–143.

Hou, P., Liu, Y., Xie, R., Ming, B., Ma, D., Li, S. and Mei, X. (2014) Temporal and spatial variation in accumulated temperature requirements of maize. *Field Crops Research*, 158, 55–64.

Hu, X., Huang, Y., Sun, W. and Yu, L. (2017) Shifts in cultivar and planting date have regulated rice growth duration under climate warming in China since the early 1980s. *Agriculture and Forest Meteorology*, 247, 34–41.

Hutchinson, M.F., McKenney, D.W., Lawrence, K., Pedlar, J.H., Hopkinson, R. F., Milewska, E. and Papadopol, P. (2009) Development and testing of Canada-wide interpolated spatial models of daily minimum–maximum temperature and precipitation for 1961–2003. *Journal of Appllied Meteorololgy and Climatology*, 48(4), 725–741.

IPCC. (2013) *IPCC Fifth Assessment Report*. Cambridge: Cambridge University Press.

Jalota, S.K., Kaur, H., Ray, S.S., Tripathi, R., Vashisht, B.B. and Bal, S.K. (2012) Mitigating future climate change effects by shifting planting dates of crops in rice–wheat cropping system. *Regional Environmental Change*, 12(4), 913–922.

Jia, X., Shao, M.a., Zhu, Y. and Luo, Y. (2017a) Soil moisture decline due to afforestation across the Loess Plateau, China. *Journal of Hydrology*, 546, 113–122.

Jia, X., Wang, Y., Shao, M.a., Luo, Y. and Zhang, C. (2017b) Estimating regional losses of soil water due to the conversion of agricultural land to forest in China's Loess Plateau. *Ecohydrology*, 10(6), e1851.

Li, Y., Yang, J., Su, Z. and Li, X. (2013) Analysis of the variation of ≥10°C accumulated temperature and its formation causes in the eastern Hetao area in the recent 50 years. *Journal of Arid Meteoroloogy*, 31(3), 511–516 (in Chinese).

Li, Y., Fan, P., Cao, Z., Chen, Y., Liu, Y., Wang, H., Liu, H., Ma, F. and Wan, H. (2017) Sand-fixation effect and micro-mechanism of remixing soil by pisha sandstone and sand in the Mu Us Sandy land, China. *Journal of Desert Research*, 37(3), 421–430 (in Chinese).

Liu, Y. (2015) Integrated land research and land resources engineering. *Resources Science*, 37(1), 1–8 (in Chinese).

Liu, Z., Yang, X., Chen, F. and Wang, E. (2013) The effects of past climate change on the northern limits of maize planting in northeast China. *Climate Change*, 117(4), 891–902.

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. and Chi, W. (2014) Spatiotemporal characteristics, patterns, and causes of land-use changes in China since the late 1980s. *Journal of Geogrphical Sciences*, 24(2), 195–210.

Liu, Y., Chen, Z., Li, Y., Feng, W. and Cao, Z. (2017a) The planting technology and industrial development prospects of forage rape in the Loess Hilly area—a case study of newly-increased cultivated land through gully land consolidation of Yan'an, Shaanxi province. *Journal of Natural Resources*, 32(12), 2065–2074 (in Chinese).

Liu, Z., Wu, C., Liu, Y., Wang, X., Fang, B., Yuan, W. and Ge, Q. (2017b) Spring green-up date derived from GIMMS3g and SPOT-VGT NDVI of winter wheat cropland in the North China Plain. *ISPRS Journal of Photogrammetry and Remote Sensing*, 130, 81–91.

Liu, Z., Wu, C., Peng, D., Wang, S., Gonsamo, A., Fang, B. and Yuan, W. (2017c) Improved modeling of gross primary production from a better representation of photosynthetic components in vegetation canopy. *Agriculture and Forest Meteorology*, 233, 222–234.

Liu, Z., Liu, Y., Wang, S., Yang, X., Wang, L., Baig, M.H.A., Chi, W. and Wang, Z. (2018) Evaluation of spatial and temporal performances of ERA-Interim precipitation and temperature in mainland China. *Journal of Climate*, 31(11), 4347–4365.

Ma, L., Zhang, T., Li, Q., Frauenfeld, O.W. and Qin, D. (2008) Evaluation of ERA-40, NCEP-1, and NCEP-2 reanalysis air temperatures with ground-based measurements in China. *Journal of Geophysical Research*, 113, D15115.

Ma, Z., Liu, H., Mi, Z., Zhang, Z., Wang, Y., Xu, W., Jiang, L. and He, J.-S. (2017) Climate warming reduces the temporal stability of plant community biomass production. *Nature Communications*, 8, 15378.

Mann, H.B. (1945) Nonparametric tests against trend. *Econometrica*, 13(3), 245–259.

Meng, Q., Liu, J., Zhang, H. and UGA. (2015) Advances in cultivation technique with film mulching in ridge and furrow in dryland farming of the Loess Plateau. *Guizhou Agriculutre Science*, 43(8), 72–82 (in Chinese).

Meng, Y., Yin, S., Yang, F. and Zhou, Y. (2016) Spatial and temporal distribution of accumulated temperature above 10°C in Shanxi-Shaanxi-Inner Mongolia region. *Chinese Journal of Agrometeorology*, 37(6), 615–622 (in Chinese).

Olesen, J.E. and Bindi, M. (2002) Consequences of climate change for European agricultural productivity, land use and policy. *European Journal of Agronomy*, 16(4), 239–262.

Ouyang, Z., Zheng, H., Xiao, Y., Polasky, S., Liu, J., Xu, W., Wang, Q., Zhang, L., Xiao, Y. and Rao, E. (2016) Improvements in ecosystem services from investments in natural capital. *Science*, 352(6292), 1455–1459.

Piao, S., Fang, J., Zhou, L., Ciais, P. and Zhu, B. (2006) Variations in satellite-derived phenology in China's temperate vegetation. *Global Change Biology*, 12(4), 672–685.

Qu, S., Wang, L., Lin, A., Zhu, H. and Yuan, M. (2018) What drives the vegetation restoration in Yangtze River basin, China: climate change or anthropogenic factors? *Ecological Indicators*, 90, 438–450.

Sun, L., Wang, S., Zhang, Y., Li, J., Wang, X., Wang, R., Lyu, W., Chen, N. and Wang, Q. (2018) Conservation agriculture based on crop rotation and tillage in the semi-arid Loess Plateau, China: effects on crop yield and soil water use. *Agriculture, Ecosystems & Environment*, 251, 67–77.

Tang, G. and Ren, G. (2005) Reanalysis of surface air temperature change of the last 100 years over China. *Climatic and Environmental Research*, 10(4), 791–798 (in Chinese).

Torriani, D.S., Calanca, P., Schmid, S., Beniston, M. and Fuhrer, J. (2007) Potential effects of changes in mean climate and climate variability on the yield of winter and spring crops in Switzerland. *Climate Reseach*, 34(1), 59–69.

Tubiello, F.N., Donatelli, M., Rosenzweig, C. and Stockle, C.O. (2000) Effects of climate change and elevated $CO_2$ on cropping systems: model predictions at two Italian locations. *European Journal of Agronomy*, 13(2), 179–189.

Wang, Y., Handoko, J. and Rimmington, G. (1992) Sensitivity of wheat growth to increased air temperature for different scenarios of ambient $CO_2$ concentration and rainfall in Victoria, Australia—a simulation study. *Climate Research*, 2(2), 131–149.

Wang, S., Fu, B., Piao, S., Lü, Y., Ciais, P., Feng, X. and Wang, Y. (2015) Reduced sediment transport in the Yellow River due to anthropogenic changes. *Nature Geoscience*, 9, 38.

Wang, S., Mo, X., Liu, Z., Baig, M.H.A. and Chi, W. (2017) Understanding long-term (1982–2013) patterns and trends in winter wheat spring green-up date over the North China Plain. *International Journal of Applied Earth Observation and Geoinformation*, 57, 235–244.

Wen, Q.H., Zhang, X., Xu, Y. and Wang, B. (2013) Detecting human influence on extreme temperatures in China. *Geophysical Research Letters*, 40(6), 1171–1176.

Wu, J. and Gao, X. (2013) A gridded daily observation dataset over China region and comparison with the other datasets. *Chinese Journal of Geophysics*, 56(4), 1102–1111 (in Chinese).

Xoplaki, E., Luterbacher, J., Paeth, H., Dietrich, D., Steiner, N., Grosjean, M. and Wanner, H. (2005) European spring and autumn temperature variability and change of extremes over the last half millennium. *Geophysical Research Letters*, 32(15), L15713.

Xu, M. and Li, Z. (2016) Accumulated temperature changes in desert region and surrounding area during 1960–2013: a case study in the Alxa Plateau, northwest China. *Environmental Earth Sciences*, 75(18), 1276.

Xu, Y., Gao, X., Shen, Y., Xu, C., Shi, Y. and Giorgi, F. (2009) A daily temperature dataset over China and its application in validating a RCM simulation. *Advances in Atmospheric Sciences*, 26(4), 763–772.

Yuan, W., Xu, B., Chen, Z., Xia, J., Xu, W., Chen, Y., Wu, X. and Fu, Y. (2014) Validation of China-wide interpolated daily climate variables from 1960 to 2011. *Theoretical and Applied Climatology*, 119(3–4), 689–700.

Yue, T., Zhao, N., Fan, Z., Li, J., Chen, C., Lu, Y., Wang, C., Xu, B. and Wilson, J. (2016) CMIP5 downscaling and its uncertainty in China. *Global and Planetary Change*, 146, 30–37.

Zhao, T. and Fu, C. (2006) Comparison of products from ERA-40, NCEP-2, and CRU with station data for summer precipitation over China. *Advances in Atmospheric Sciences*, 23(4), 593–604.

Zhou, B., Xu, Y., Wu, J., Dong, S. and Shi, Y. (2016) Changes in temperature and precipitation extreme indices over China: analysis of a high-resolution grid dataset. *International Journal of Climatology*, 36(3), 1051–1066.

## SUPPORTING INFORMATION

Additional supporting information may be found online in the Supporting Information section at the end of the article.

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## APPENDIX A: MANN–KENDALL NONPARAMETRIC STATISTICAL METHOD

The detailed calculation steps of Mann–Kendall nonparametric statistical method were showed as follows:

$$S_k = \sum_{i=1}^{k} r_i, r_i = \begin{cases} 1, x_i > x_j \\ 0, x_i \le x_j \end{cases} (1 \le j \le i; 2 \le k \le n), \tag{A1}$$

$$\begin{cases} \text{mean}(S_k) = \dfrac{k(k-1)}{4} \\ \text{var}(S_k) = \dfrac{k(k-1)(2k-5)}{72} \end{cases} (2 \le k \le n), \tag{A2}$$

$$\text{UF}_k = \begin{cases} \dfrac{S_k - \text{mean}(S_k)}{\sqrt{\text{var}(S_k)}} (2 \le k \le n) \\ 0 \qquad (k=1) \end{cases}, \tag{A3}$$

where the climatic sequences are set as $x_1, x_2, \ldots, x_n$; $S_k$ are the cumulative amount of the ith sample; $r_i$ are a temporary variable; $n$ is the number of sample; mean($S_k$) and var($S_k$) are mean and variance of $S_k$, respectively; and UF$_k$ represent the standardized $S_k$. If $|\text{UF}_k| > U_\alpha$ (when $\alpha$ is 0.05, the corresponding $U_\alpha$ is equal to 1.96), it implies that the series has a significant trend (namely, $p < 0.05$). By using the method of inverted sequence, $x_n, x_{n-1}, \ldots, x_1$ are expressed as $x'_1, x'_2, \ldots, x'_n$. Similarly, we used the formulas (A1)–(A3) to compute $r'_i$, $S'_k$, mean$\left(S'_k\right)$, var$\left(S'_k\right)$ and UF$'_k$, of which UB0$_k = -$UF$'_k$. UB$_k$ are finally the inverted sequence of UB0$_k$. This study chose $\alpha = 0.05$ as the significant level. If UF value of the variable is beyond the confidence area limits, it suggests that variations of the variable reach the significance at the 0.05 level. Also, if UF and UB cross into the confidence area, the point of intersection is the mutation point for the variable. The mutation point divides the entire period into two periods if the number of mutation point is one. The data of two periods usually have different trends.