ORIGINAL PAPER

Changes in wheat potential productivity and drought severity in Southwest China

Di He[1] · Jing Wang[1] · Zhihua Pan[1] · Tong Dai[1] · Enli Wang[2] · Jianping Zhang[3]

Abstract Wheat production in Southwest China (SWC) plays a vital role in guaranteeing local grain security, but it is threatened by increasingly frequent seasonal drought in recent years. In spite of the importance, the impact of past climate change on wheat potential productivity and drought severity has not been properly addressed. In this study, we employed a relatively simple resource use efficiency model to analyze the spatiotemporal changes of the potential productivity (PP) and rainfed productivity (RP) of wheat (*Triticum aestivum* L.) in Southwest China (SWC) from 1962 to 2010. A wheat drought severity index was defined as the relative difference between PP and RP, i.e., (PP-RP)/PP, to evaluate the changing frequency and severity of drought under warming SWC. Across the entire region from 1962 to 2010, the negative impact of decreasing sunshine hours (0.06 h day^{-1} per decade, $p < 0.05$) on PP was offset by the increase in average temperature of wheat growing season (0.22 °C per decade, $p < 0.01$). PP increased by 283 kg ha^{-1} per decade ($p < 0.01$), while RP did not show significant trend due to increased water stress. The gap between PP and RP has increased by 26 kg ha^{-1} per decade ($p < 0.01$). Moderate and severe drought mostly occurred in central and southern SWC. The percentage of stations experienced moderate or severe drought increased by 2.0 % ($p < 0.05$) per decade, and reached 52 % in recent decade.

✉ Jing Wang
  wangj@cau.edu.cn

[1] College of Resources and Environmental Sciences, China Agricultural University, Beijing 100193, China

[2] CSIRO Agriculture, G.P.O. Box 1666, Canberra, ACT 2601, Australia

[3] Chongqing Institute of Meteorological Sciences, Chongqing 401147, China

Our results, together with the uneven distribution of rainfall, indicate great potential for irrigation development to harvest water and increase wheat yield under the warming climate in SWC.

1 Introduction

Southwest China (SWC), comprising Chongqing City, Yunnan, Guizhou, and Sichuan provinces, is one of the typical grain, oil, and sugar production areas of China. The planting area of wheat in SWC is about 2.2 million ha, accounting for 9.2 % of the national total, nearly 80 % of which was in Sichuan and Yunnan provinces (National Bureau of Statistics of China 2009). The dominant cropping system in SWC is a wheat–rice double rotation, where wheat is sown in autumn and harvested in spring. Wheat production plays a vital role in guaranteeing local grain security. However, wheat yield in SWC is threatened by increasingly frequent winter and spring drought events (Zhang et al. 2012), raising concerns about food security in the region. Statistics showed that the drought frequency from 1961 to 2011 was nearly 50 % in SWC, i.e., drought occurred in almost half of the years (Wang et al. 2015a). The drought affected areas in SWC have increased by a rate of 2.2 % per decade from 1951 to 2010 (Yu et al. 2014). In order to develop effective mitigation strategies to advance crop yield, the spatiotemporal change of drought severity and its impact on wheat productivity during the past decades need to be better understood. However, there is a lack of studies to evaluate the changes in drought severity and yield potential of wheat under the warming SWC.

Previous work on evaluation of drought was mostly based on the estimation of water balance and supply/demand terms, involving the calculation of total rainfall, evapotranspiration, runoff, etc. to determine drought severity indices (Heim 2002;

Andreadis and Lettenmaier 2006; Wang et al. 2007; Huo et al. 2013). Indices related to reference evapotranspiration (ET₀), as compared to rainfall (supply), are widely used because these integrate the impacts of climate factors on crop water requirement (Thornthwaite 1948; Vicente-Serrano et al. 2010; Anderson et al. 2011; Huo et al. 2013). However, most of these assessments were often based on the difference between annual or growing season crop water demand and rainfall supply, which cannot reflect the impact of intra-seasonal drought on crop growth. In humid and semi-humid regions, e.g., Southwest China, seasonal/intra-seasonal drought is the major cause for crop yield loss. In such region, evaluation of crop drought severity must consider the impact of uneven rainfall distribution during crop growing season. For the drought index to be reliable, it should also be linked to changes in crop yield (Zhao et al. 2012).

Drought severity of wheat can be linked to the yield loss under rainfed conditions as compared to the yield potential under well-watered conditions. Therefore, the concept of potential productivity (maximum yield under well-watered and stress-free conditions) and rainfed productivity (maximum yield under rainfed conditions free of other stresses) is used here to develop wheat drought severity index. The potential productivity integrates the impact of changing radiation and temperature on crop yield, while the rainfed productivity integrates, in addition, the impact of crop water deficit caused by insufficient rainfall and uneven rainfall distribution on crop yield (Wang et al. 2011, 2012a). Spatiotemporal changes in wheat potential productivity has been widely analyzed in northern parts of China using empirical methods (Huang 1985; Qin et al. 2013a) and crop growth models (Anderson et al. 2011; Liu et al. 2012; Lu and Fan 2013). In SWC, significant warming has been detected over the last five decades (Qiu 2010; He et al. 2014). But there is still a lack of studies on the impact of past climate change on wheat yield potential and wheat drought severity.

The objectives of this study are to (i) investigate the spatiotemporal patterns of past climate changes and their impact on wheat potential productivity, (ii) evaluate drought severity of wheat by defining an index linking to wheat potential and rainfed productivity, and (iii) analyze the spatiotemporal changes of the frequency and severity of wheat drought in the period of 1962–2010.

2 Materials and methods

2.1 Climate, study sites, and crop data

SWC is largely characterized by subtropical humid monsoon climate, with annual average temperature of 14.2 °C and annual rainfall of 1049 mm (1961 to 2010). Winter wheat is planted in autumn (October to November) and harvested in spring (April to May).

In this study, 64 meteorological sites in SWC were selected from the National Meteorological Networks managed by China Meteorological Administration (CMA). CMA has consistent observation and quality control standards for collecting and analyzing these surface climate data (Wang et al. 2015b). Historical daily weather data from 1961 to 2010, including daily average, maximum, and minimum temperatures (°C); precipitation (mm); sunshine hours (h day⁻¹); relative humidity (%); and wind speed (m s⁻¹) were available from these stations. Wheat phenological stages dataset, i.e., time of sowing, tilling, heading, grain filling, and maturity were obtained from 66 agricultural meteorological sites and most of them share the same locations with meteorological sites (Fig. 1). All the data were recorded with consistent CMA data collection standards (Liu et al. 2012). Both the meteorological and agricultural meteorological sites are evenly distributed throughout SWC and cover the main wheat production regions (Fig. 1).

The whole study area was divided into five wheat-growing districts, i.e., I, II, III, IV, and V, based on the sowing dates and growth durations of wheat from 2012 to 2013 (Fig. 1). Sowing dates in districts I, II, III, IV, and V are 7–16 October, 24–31 October, 1–8 November, 12–16 November, and 20–31 October, respectively. The corresponding average growth durations were 190, 195, 190, 180, and 170 days, respectively. The average sowing dates and lengths of each developmental stages of wheat were used to calculate productivity potential in each wheat-growing district (Table 1).

2.2 Calculation of wheat potential and rainfed productivity

The potential and rainfed productivity of wheat was calculated using a simple method based on radiation, temperature, and rainfall during each of the developmental stages of wheat (Huang 1985; He et al. 2014). The method first estimates the photosynthetic productivity, which is then reduced by considering the impact of suboptimal temperatures and water shortage (Huang 1985; Yuan et al. 2012). This method has been widely used in estimating crop productivity in China (Yang et al. 2010; Yuan et al. 2012; He et al. 2014).

The potential productivity (PP; 10^3 kg ha⁻¹) represents the maximum potential yield under stress-free condition and is determined by radiation and temperature:

$$PP = \sum_{j=1}^{4} \left(\sum_{i=1}^{gd_j} \left(0.219 \times C \times R_{s,i} \times f(T_i) \right) \right) \quad (1)$$

where 0.219 is the Bingwei Huang coefficient in unit of 10^{-5} kg kJ⁻¹ (He et al. 2014), and C is the crop harvest index,
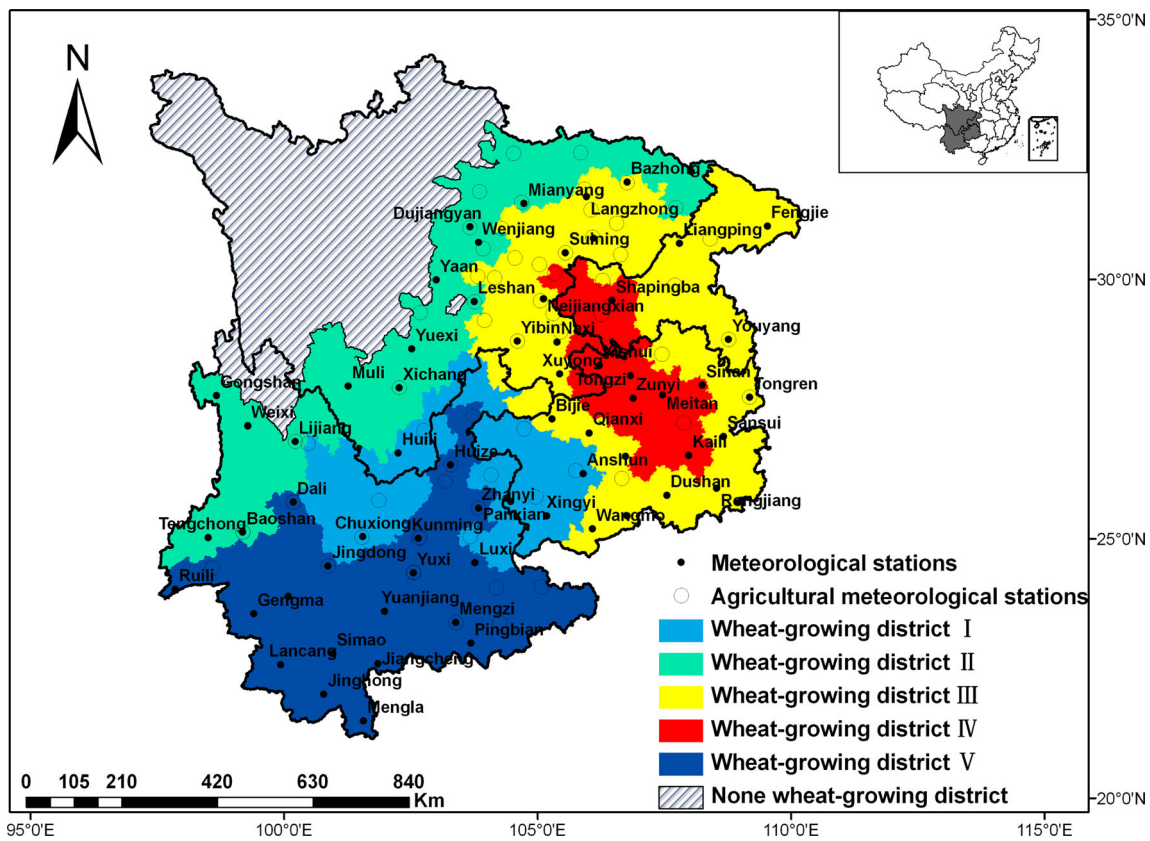
Fig. 1 Southwest China and the study region. The region was divided into five wheat-growing districts based on the sowing time and wheat growing periods

taking the value of 0.35 for wheat (Qin et al. 2013b). j represents each wheat stage (sowing–tillering, tillering–heading, heading–start grain filling, and start grain filling–maturity), and gd_j is the length of each stage.

$R_{s,i}$ is the daily solar radiation in units of kJ cm^{-2} day^{-1}, calculated as:

$$R_{s,i} = (a_s + b_s \times n_i/N_i)R_{a,i} \quad (2)$$

where $R_{a,i}$ is the daily extraterrestrial radiation in kJ cm^{-2} day^{-1}, n_i is the daily actual duration of sunshine in hours, and N_i is the daily maximum possible duration of sunshine in hours. $a_s = 0.25$

and $b_s = 0.50$ are used for the estimation of $R_{s,i}$, as recommended in Allen et al. (1998).

$f(T_i)$ is the temperature stress coefficient, calculated as follows (He et al. 2014):

$$f(T_i) = \begin{cases} 0 & T_i < T_{\min,j}, T_i > T_{\max,j} \\ \dfrac{T_i - T_{\min,j}}{T_{o,j} - T_{\min,j}} & T_{\min,j} \leq T_i < T_{o,j} \\ \dfrac{T_{\max,j} - T_i}{T_{\max,j} - T_{o,j}} & T_{o,j} \leq T_i \leq T_{\max,j} \end{cases} \quad (3)$$

where T_i is the daily average temperature in °C, and $T_{\min,j}$, $T_{\max,j}$, and $T_{o,j}$ are the minimum, maximum, and optimum

Table 1 Average sowing dates and lengths of the four wheat developmental stages used for wheat productivity potential simulation in each wheat-growing district (days)

District	Sowing date	Initial stage (sowing–tillering)	Development stage (tillering–heading)	Middle stage (heading–start grain filling)	Late stage (start grain filling–maturity)	Total
I	Oct 10	30	90	40	30	190
II	Oct 25	35	90	40	30	195
III	Nov 5	30	90	40	30	190
IV	Nov 15	30	85	40	30	180
V	Oct 25	30	70	40	30	170

temperatures for wheat growth in each of the developmental stages in °C, respectively. The values of $T_{min,j}$, $T_{max,j}$, and $T_{o,j}$ (Table 2) were derived according to Porter and Gawith (1999) and Wang et al. (2012a).

The rainfed productivity (RP; 10^3 kg ha^{-1}) represents the maximum yield that can be achieved under local rainfall conditions and is calculated by correcting the potential productivity with the water stress coefficient (He et al. 2014):

$$\text{RP} = \sum_{j=1}^{4} \left(\sum_{i=1}^{gd_j} \left(0.219 \times C \times R_{s,i} \times f(T_i) \right) \times f(W_j) \right) \quad (4)$$

Here, $f(W_j)$ is the water stress coefficient, calculated as:

$$f(W_j) = \begin{cases} P_j / \text{ET}_{c,j} & 0 \le P_j < \text{ET}_{c,j} \\ 1 & P_j \ge \text{ET}_{c,j} \end{cases} \quad (5)$$

where P_j is the total precipitation during each wheat stage in millimeter. $\text{ET}_{c,j}$ is the total wheat water requirement during each wheat stage in millimeter, which can be calculated as:

$$\text{ET}_{c,j} = \sum_{i=1}^{gd_j} \left(\text{ET}_{0,i} \times K_{c,i} \right) \quad (6)$$

where $K_{c,i}$ is the daily crop coefficient interpolated from the three threshold values of 0.7, 1.15, and 0.4 as recommended in Allen et al. (1998). In the initial (sowing–tillering) and middle stages (heading–start grain filling), $K_{c,i}$ is stable as 0.7 and 1.15, respectively. From tillering to heading and from start grain filling to maturity, i.e., the development and late stage, $K_{c,i}$ is interpolated linearly, respectively, between 0.7 and 1.15 and between 1.15 and 0.4. $\text{ET}_{0,i}$ is the reference crop evapotranspiration in mm day^{-1} and calculated using the FAO Penman–Monteith equation (Allen et al. 1998).

$$\text{ET}_{0,i} = \frac{0.408\Delta(R_n - G) + 900\gamma U_2(e_s - e_a)/(T + 273)}{\Delta + \gamma(1 + 0.34U_2)} \quad (7)$$

where $\text{ET}_{0,i}$ is the daily reference crop evapotranspiration in mm day^{-1}; R_n is the net radiation in MJ m^{-2} day^{-1}; G is the soil heat flux in MJ m^{-2} day^{-1}; T is the daily average temperature at 2-m height in °C; U_2 is the wind speed at 2-m height in

m s^{-1}; e_s is the saturated water vapor pressure in kPa; e_a is the actual water vapor pressure in kPa; Δ is the slope of the saturation vapor pressure versus temperature relationship in kPa °C^{-1}; and γ is the psychrometric constant in kPa °C^{-1}. R_n is the difference between the incoming net shortwave radiation and the outgoing net long wave radiation. Wind speed measured at 10-m height was adjusted to 2-m height using a logarithmic wind speed profile (Allen et al. 1998). ET_0 was calculated in daily time steps, and G was negligible and assumed to be zero in this study (Allen et al. 1998). More details about this method are given by He et al. (2014).

2.3 Wheat drought severity

In this study, wheat drought severity (WDS) was defined as the relative difference between potential and rainfed productivity of wheat:

$$\text{WDS} = (\text{PP} - \text{RP})/\text{PP} \times 100\% \quad (8)$$

WDS ranges between 0 and 1. It can represent the loss of wheat potential productivity due to water stress caused by either insufficient precipitation or uneven precipitation distribution during wheat growing season. A larger WDS represents more severe drought for wheat.

A uniform classification of drought severity for SWC was constructed based on the mean and standard deviation of WDS for 64 stations over 1962–2010. For each station, WDS_{mean} was calculated as the mean value of WDS from 1962 to 2010. Across 64 stations, WDS_{all} was calculated as the mean value, while σ_{WDS} was the standard deviation of the 64 WDS_{mean}. Drought severity was assumed to exhibit a normal distribution across SWC, similar to the criterion used for drought severity assessment by Zhao et al. (2012) in Henan province of China. We classified the wheat drought severity for a specified station in a given year based on WDS as mild drought ($\text{WDS}_{all} - \sigma_{WDS} \le \text{WDS} < \text{WDS}_{all}$), moderate drought ($\text{WDS}_{all} \le \text{WDS} < \text{WDS}_{all} + \sigma_{WDS}$), and severe drought ($\text{WDS} \ge \text{WDS}_{all} + \sigma_{WDS}$).

2.4 The statistical and spatial analysis

Linear regression method was used for trend analysis of climate factors and potential productivity. Linear regression is a commonly used parametric method for identifying linear trend in a time series and has been widely used to analyses the change trend of climatic variables and yield potential (Liu et al. 2012, 2013). The slope of the linear regression equation indicates the mean temporal change of the studied variables. Multiplying the slope by the number of years can obtain the total change during the period. A Student's t test (two tailed) was used to assess the significance of the change trends. The coefficient of variation of productivity was defined as the

Table 2 Minimum (T_{min}), maximum (T_{max}), and optimum (T_o) temperatures for wheat growth in each of the wheat developmental stages (°C)

Stage	T_{min}	T_{max}	T_o
Initial (sowing–tillering)	6	24	16
Development (tillering–heading)	5	27	15
Middle (heading–start grain filling)	11	33	20
Late (start grain filling–maturity)	12	35	23

standard deviation divided by the mean and was calculated for each station (Wu et al. 2006).

The point-level results of detected climatic variables, wheat potential and rainfed productivity and their differences, and WDS were spatially interpolated by applying inverse distance weighting (IDW) interpolation method, which is a popular interpolation method for large areas and moderate station density (Gemmer et al. 2004). This enabled the spatial presentations of past climate change and its impact on potential productivity and drought severity across SWC.

3 Results

3.1 Spatiotemporal trends of climate variables during wheat growing season

Growing season average and maximum temperatures ranged from 7.0 to 19.7 °C (11.7 ± 2.8 °C, i.e., with a mean of 11.7 °C and a standard deviation of 2.8 °C) and from 11.2 to 27.7 °C (17.4 ± 4.0 °C), respectively. The highest values mostly occurred in the south of SWC (Fig. 2a, c). Growing season minimum temperature ranged from 1.6 to 14.7 °C (7.7 ± 2.7 °C), and the highest values occurred in the south and northeast of SWC (Fig. 2b). Growing season precipitation

increased from west to east SWC, ranging from 56.6 to 744.8 mm (238 ± 110 mm). The areas with low growing season precipitation were mostly in Yunnan Province and in the south of Sichuan Province (Fig. 2d). Growing season average sunshine hours ranged from 1.8 to 8.0 h day^{-1} (4.3 ± 2.2 h day^{-1}), and the highest values occurred in the southwest SWC (Fig. 2e). Reference crop evapotranspiration varied from 291.4 to 744.3 mm (449 ± 120.7 mm). Central part of Yunnan Province showed higher potential evaporation capacity (Fig. 2f).

Across SWC, growing season average, minimum, and maximum temperatures showed significant ($p < 0.01$) increasing trend at 38, 84, and 34 % of the selected stations. As regional average, average and minimum temperatures increased ($p < 0.01$) by 0.22 and 0.29 °C per decade, respectively, while the average maximum temperature did not show significant trend (Fig. 3a–c). The largest increase in average and minimum temperatures occurred in Yunnan Province (Fig. 3a, b). Opposite local trend occurred significantly at Gengma in Yunnan Province where average temperature decreased by 0.33 °C ($p < 0.01$) per decade (Fig. 3a–c). Growing season precipitation showed a decreasing trend at 67 % of the stations, but only 9 % of which were statistically significant (Fig. 3d). Northern SWC exhibited the largest decrease in average sunshine hours, while southern and central parts
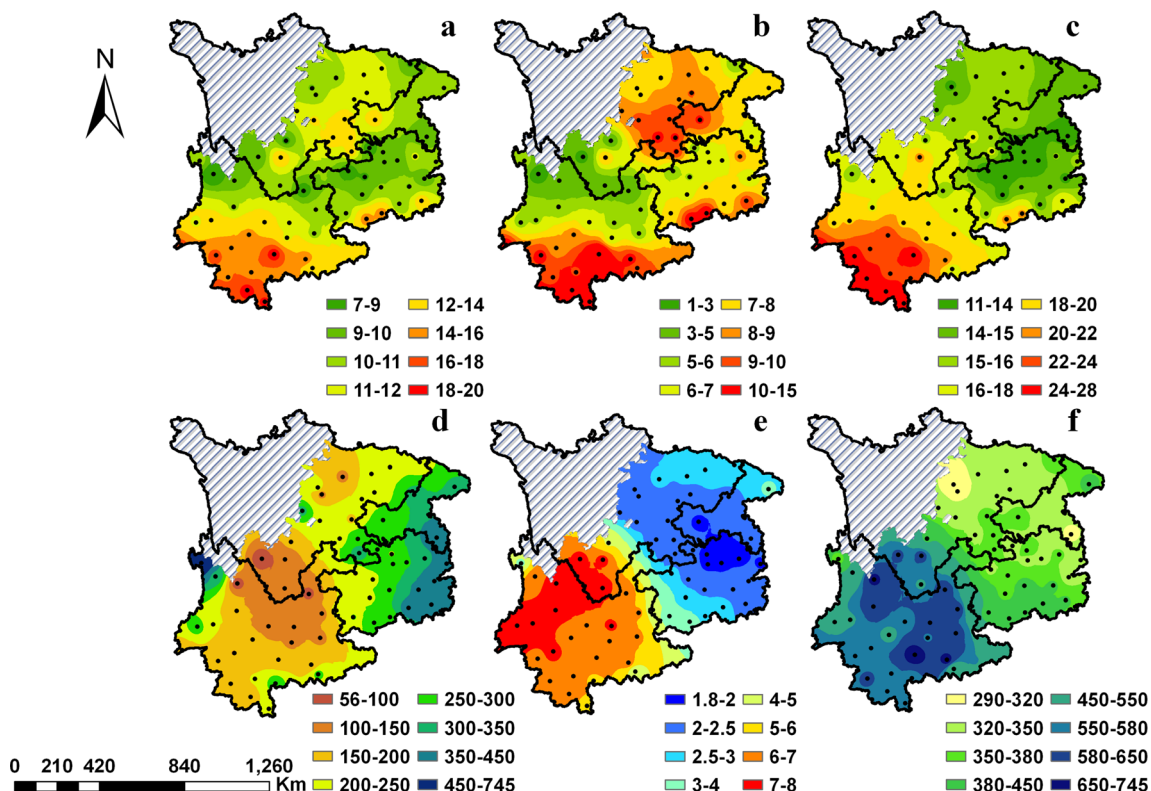

Fig. 2 Geospatial gradients of long-term mean climate factors, i.e., average temperature (**a**, °C), minimum temperature (**b**, °C), and maximum temperature (**c**, °C), precipitation (**d**, mm), sunshine hours (**e**, h day^{-1}), and reference crop evapotranspiration (**f**, mm) during wheat growing season in Southwest China from 1962 to 2010
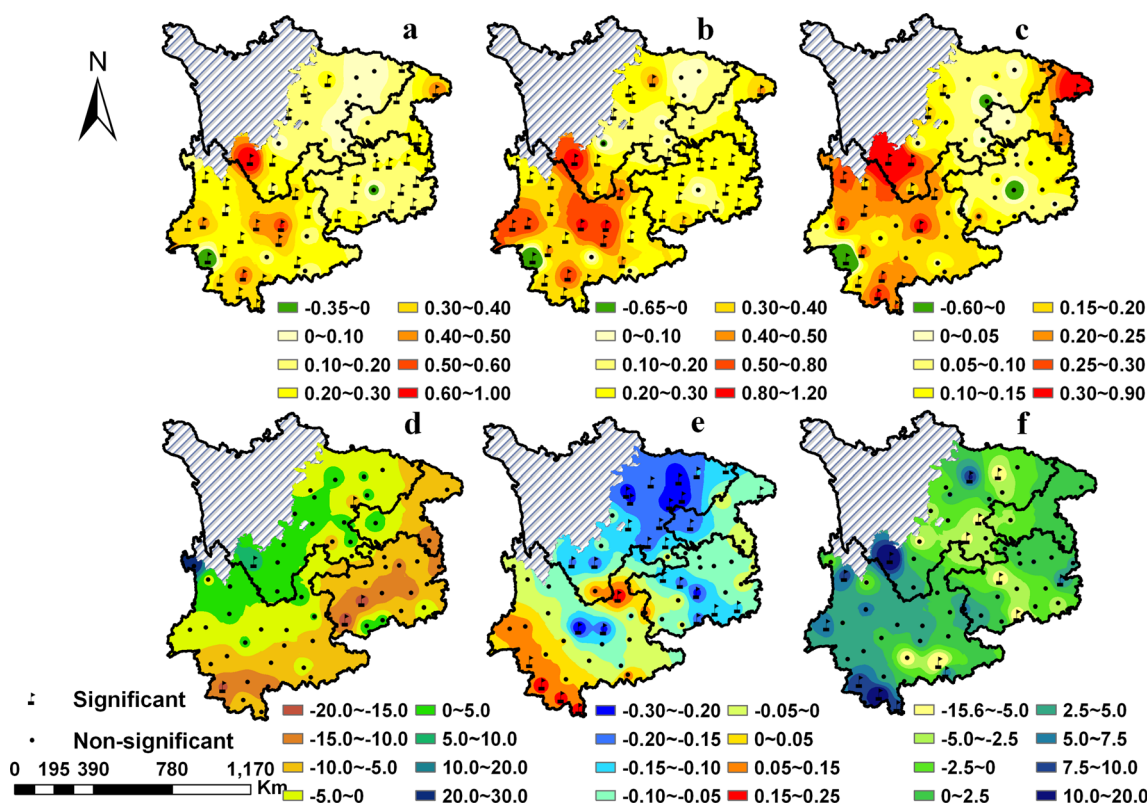
Fig. 3 The rates of change in **a** average temperature (°C per decade), **b** minimum temperature (°C per decade), **c** maximum temperature (°C per decade), **d** precipitation (mm per decade), **e** sunshine hours (h day^{-1} per decade), and **f** reference crop evapotranspiration (mm per decade) during wheat growing season in Southwest China from 1962 to 2010

showed a significant increase trend ($p < 0.05$; Fig. 3e). Change in growing season reference crop evapotranspiration did not show significant trend (Fig. 3f).

3.2 Changes in wheat potential and rainfed productivity and their difference

Wheat potential productivity increased from north to south, ranging from 1902 to 16,843 kg ha^{-1}. The highest values mostly occurred in wheat-growing district V due to higher growing season radiation and temperature (Figs. 2a–c, e, and 4a). The rainfed productivity of wheat was noticeably lower than the potential productivity, ranging from 723 to 8113 kg ha^{-1} (Fig. 4a, b). Regional mean potential and rainfed productivity of wheat were 8219 and 4271 kg ha^{-1}, with coefficients of variation of 11.9 and 13.4 %, respectively (Fig. 4a, b). The lowest values of rainfed productivity were located in the central of SWC, with a similar distribution pattern to growing season precipitation (Figs. 2d and 4b). Its coefficient of variation (ranging from 12 to 86 %) was higher than that of the potential productivity (ranging from 6 to 66 %), demonstrating high inter-annual variation in wheat growing season precipitation. The gap between the potential and rainfed productivity varied considerably inter-annually and with locations (between 208 and 13,243 kg ha^{-1}). The gap reached 4000 to 13,200 kg ha^{-1}

in central and southern SWC (Yunnan and Sichuan provinces) (Fig. 4c), where growing season precipitation was a strong limiting factor for wheat potential productivity.

From 1962 to 2010, the potential productivity showed an increasing trend at 78 % of the study stations, with 48 % of them statistically significant ($p < 0.05$) (Fig. 4d). Across SWC, it increased by 283 kg ha^{-1} per decade ($p < 0.05$), with the largest increase mostly in the central and southern areas of SWC (Fig. 4d). The negative impact of decreasing solar radiation on potential productivity was offset by the increase in temperature, especially in Yunnan Province and southern part of Sichuan Province. However, for the rainfed productivity, at only 16 % of stations, it did show a statistically significant increase ($p < 0.05$). Averaged across SWC, the rainfed productivity did not change significantly, while in the southern part, it showed a significant ($p < 0.05$) decreasing trend due to increasing water stress during wheat growing season (Fig. 4e). The gap between potential and rainfed productivity showed an increasing trend at 77 % of the stations, with 43 % of them being statistically significant ($p < 0.05$; Fig. 4f). For the entire SWC, the productivity gap increased by 26 kg ha^{-1} per decade ($p < 0.01$). The central and southern areas, where the potential productivity showed a significant increasing trend, witnessed a significant increasing trend in the productivity gap from 1962 to 2010 (Fig. 4d, f).
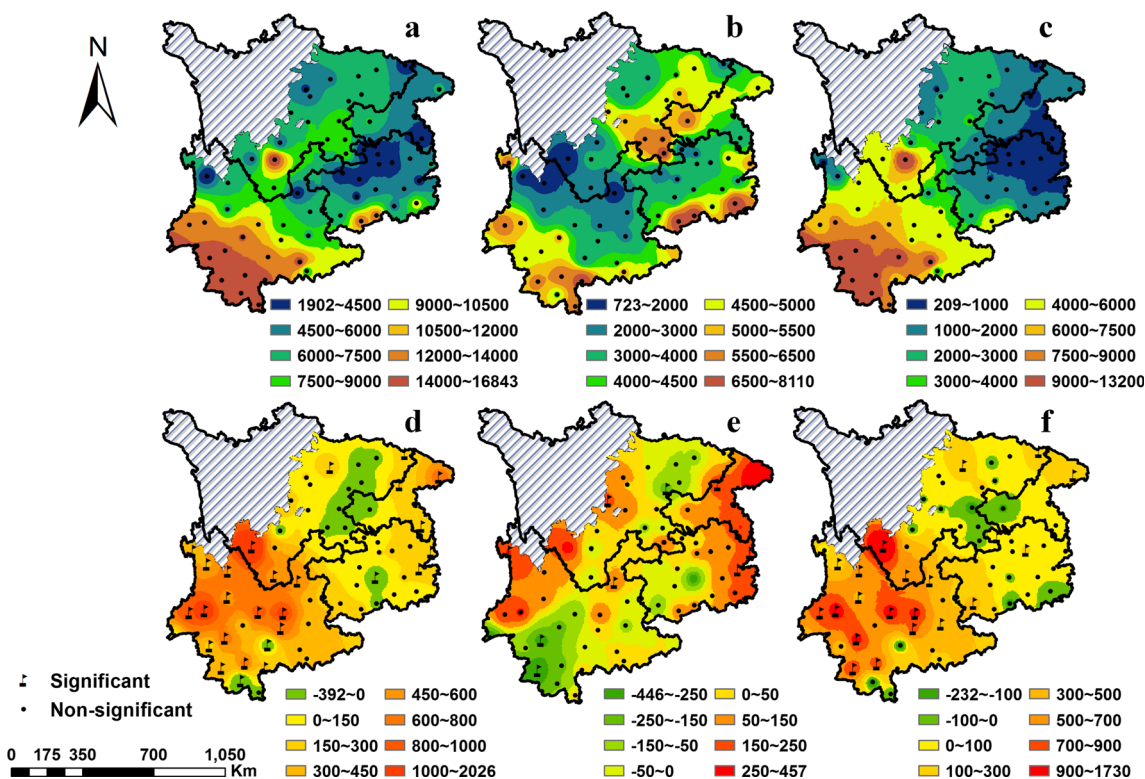
Fig. 4 **a** The potential productivity, **b** the rainfed productivity, and **c** the gap between the two (kg ha^{-1}) of wheat averaged from 1962 to 2010. **d**–**f** The rates of change (kg ha^{-1} per decade) of **a**–**c** in Southwest China from 1962 to 2010, respectively

3.3 Changes in wheat drought severity and drought frequency in SWC

Wheat drought severity (WDS) varied considerably with location and from year to year (between 7 and 90 %). Mild drought mostly occurred in eastern part of SWC (Fig. 5a), where WDS were less than 30 % and precipitation could meet water requirement of wheat in most seasons. Stations with moderate and severe drought were located at central and southern part of SWC (Fig. 5a) , where WDS was more than 70 %. Generally, distribution pattern of drought severities was similar to that of growing season precipitation, but there were some differences in several stations. For instance, at Simao in Yunnan and Suining in Sichuan, the growing season precipitation are similar (202 and 200 mm), but the WDS was significantly different (60 %, moderate drought in Simao; 34 %, mild drought in Suining) due to the contrasting seasonal rainfall distribution.

From 1962 to 2010, WDS showed increasing trends at 78 % of the stations, but the trends were only statistically significant ($p < 0.05$) at 14 % of stations (Fig. 5b). Wanyuan, located in Sichuan Province, witnessed the largest rate of increase trend (4.7 % per decade) from 1962 to 2010, due to its location in mild drought area with a relative low WDS value (23 %).

Percentage of stations with moderate and severe drought showed an increase trend at the rate of 2.0 % per decade ($p < 0.05$) from 1962 to 2010. There has been a significant temporal change in the numbers of stations with moderate and severe drought during the past 50 years (Fig. 6). In the 2000s, there were 334 times of moderate and severe drought occurring, while only 283 times in the 1990s in 64 selected stations. Percentage of stations with moderate and severe drought reached 64 % in 2010, which was the second highest value following 66 % in 1987 in the 50 years. At Lijiang in Sichuan province and Muli in Yunnan Province, severe drought occurred at highest incidence in 96 % of wheat growing seasons during the past 50 years.

4 Discussion

In this study, we adopted a relatively simple method and used fixed length of wheat growing season for the past 50 years to assess the impact of past climate change on wheat potential and rainfed productivity. Our method contrasts with the more process-based crop modeling approach in that it does not require detailed crop and soil data for model calibration. Process-based models include a large number of biophysical parameters that require calibration within realistic bounds (Holzkämper et al. 2015). In addition, crop growth model applications are typically confronted with large uncertainty in the spatial distribution of soil properties, initial conditions, and crop parameters (De Wit and Van Diepen 2007). In that sense, the method used here is better suited for regional evaluation of wheat potential

Fig. 5 Spatial distribution of wheat drought severity (**a**), and its rate of change (**b**, % per decade) in Southwest China from 1962 to 2010
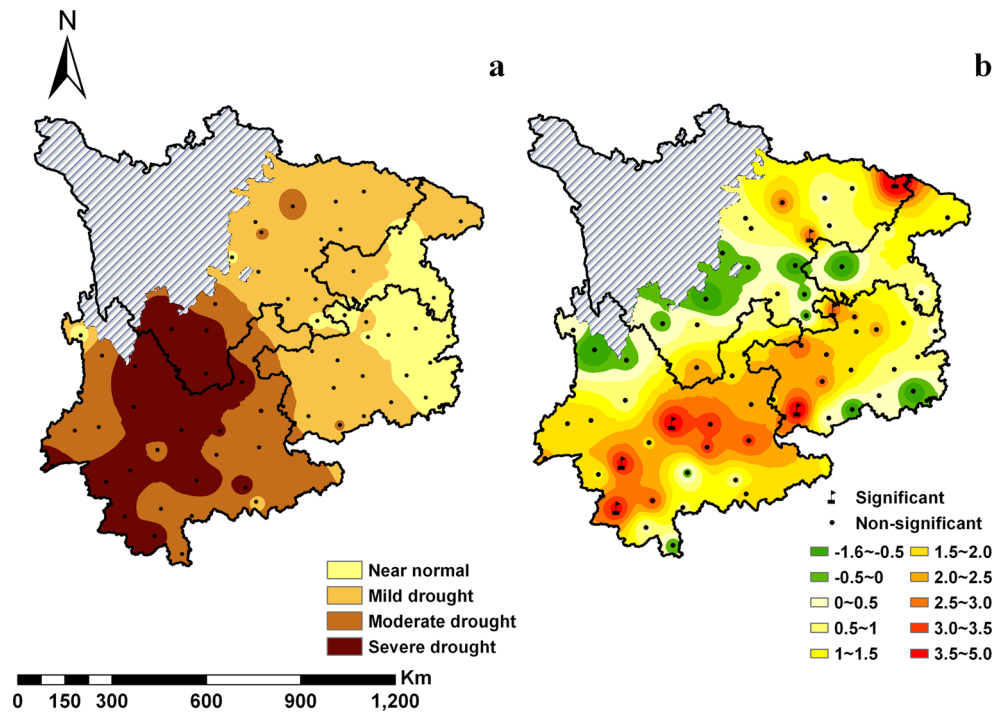
productivity and drought severity, particularly in areas with limited data like SWC (Yuan et al. 2012).

While relatively simple, our approach still captures the interactions of the key drivers, i.e., radiation, temperature, and water supply/demand ratio, as they impact on wheat growth in different stages of wheat development. This captures not only the impact of variations in radiation and temperature but also the impact of rainfall distribution on wheat growth. Thus, the defined WDS index better reflects the impact of seasonal drought and uneven rainfall distribution than the indices of previous studies (Li et al. 2009; Huo et al. 2013; Yu et al.

2014). For instance, at Pingbian and Wangmo, the growing season precipitation (382 and 384 mm) and wheat water requirements (268 and 267 mm) are similar, while WDS in Pingbian and Wangmo were 35 % (mild drought) and 42 % (moderate drought), which resulted from uneven distribution of rainfall within wheat growing season.

While some previous studies indicated that warming trend (i.e., increase in temperature) has reduced crop growth duration (Tao et al. 2006; You et al. 2009), more recent studies showed that autonomous adoption of new wheat varieties was able to compensate the negative impact of climate warming on

Fig. 6 Percentage of stations with moderate and severe drought and times of moderate and severe drought occurred per decade (1960s is from 1962 to 1970) in Southwest China from 1962 to 2010. Asterisk indicates statistical significance at $p < 0.05$
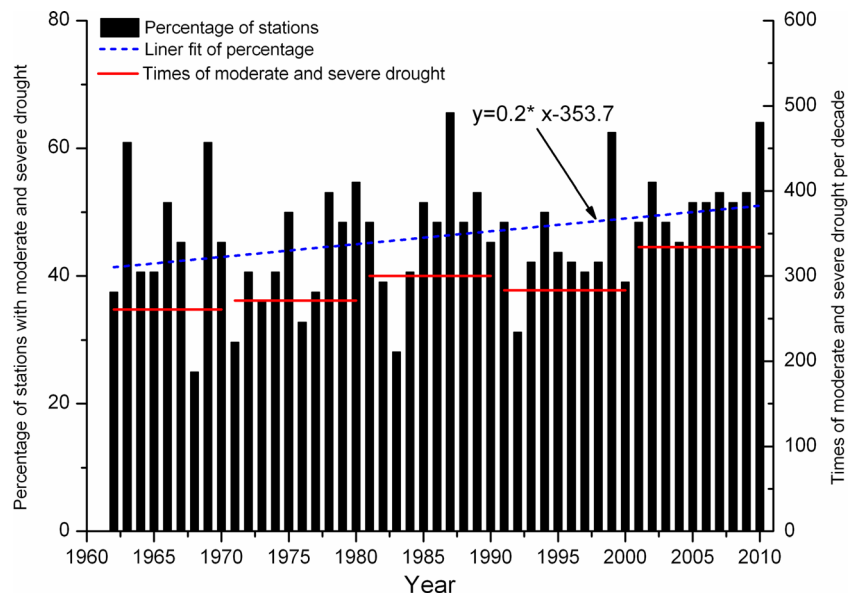
crop growing duration (Liu et al. 2010; Wang et al. 2012b, 2013). In addition, field-scale experiments suggested that winter wheat might adjust its growth to partly compensate for the negative effects from warming (Hou et al. 2012). Thus, use of fixing crop duration can be justified, which defines the maximum growing season for improved crop cultivars.

Our estimated wheat potential and rainfed productivity seems to be higher than expected as compared to actual wheat yield in some regions. This can be caused by the use of a constant radiation conversion ratio (0.219) for the whole crop season and ignoring the dynamics of LAI development. However, the potential productivity represents the maximum potential of wheat yield assuming full utilization of the resources in the growing season, and the possible overestimation does not invalidate our results on the trends of productivity and drought severity. The very high potential yield and yield gap in the southwest corner of the study region were largely influenced by the extremely high values calculated for a few sites, which may further reflect deficiencies of this empirical approach for estimating yield under very dry conditions. Improvement of the estimations of potential productivity can be achieved with more available crop data in the future.

Our results revealed that across the entire SWC, averaged rainfed productivity of wheat was only 52 % of the potential productivity (1962 to 2010). The gap between the two varied spatially from 208 to 13,243 kg ha^{-1}. This gap was much larger than the gap for maize crop in the same region, which was found to be in a range from 12 to 2729 kg ha^{-1} in one of our previous studies (He et al. 2014). Due to the relatively high rainfall in the maize growing season (412 to 608 mm), the gap between potential and rainfed productivity of maize was mainly caused by uneven distribution of rainfall (He et al. 2014). For wheat, however, the large gap between potential and rainfed productivity was caused by both the insufficient amount and the uneven distribution of rainfall within growing season. In eastern SWC, rainfall in wheat growing season is generally more than 300 mm, and the uneven distribution of rainfall leads to low water use efficiency and thus limits wheat yield. In central SWC, insufficient growing season precipitation (less than 150 mm) is the main limiting factor for wheat productivity (less than 2000 kg ha^{-1}) (Figs. 2d and 4b).

The significant water stress and yield reduction under rainfed conditions indicate that irrigation development is an efficient means to increase wheat productivity. However, irrigation has been practiced in only 24 % of the total crop production areas in SWC (National Bureau of Statistics of China 2009). For wheat, only few areas in central SWC were irrigated, where growing season rainfall limits wheat production seriously (such as Muli and Lijiang cities; Figs. 2d and 4c) (He and Wang 2015). In addition, this study reveals a noticeable increase in the gap between potential and rainfed productivity of wheat under the warming climate in both central and southern SWC (Fig. 4f). This implies a great potential to further increase wheat yield through irrigation development under warming climate as an effective adaptation method. The high and uneven distribution of rainfall in these regions would support the development of technologies to collect and store rainfall and runoff water for irrigation use during dry seasons, which has been widely practiced in arid and semi-arid region (Pandey et al. 2003; Abdulla and Al-Shareef 2009).

5 Conclusion

Our analysis of the geospatial and temporal trends of wheat potential and rainfed productivity of wheat revealed a distinct gap between the two in large parts of the SWC, and the gap has become larger under warming climate from 1961 to 2010. In addition, wheat drought severity (WDS), defined as the relative difference between the potential and rainfed productivity of wheat, became larger and frequency of moderate and severe drought increased. The high and uneven rainfall in this area implies that there is great potential for irrigation development by collecting and storing rainfall and runoff water to increase wheat yield. The results can assist in long-term policy development for agriculture and water resource management in SWC.

References

Abdulla FA, Al-Shareef AW (2009) Roof rainwater harvesting systems for household water supply in Jordan. Desalination 243:195–207. doi:10.1016/j.desal.2008.05.013

Allen RG, Pereira LS, Raes D, Smith M (1998) Crop evapotranspiration—guidelines for computing crop water requirements—FAO irrigation and drainage paper 56. Irrig Drain 1–15. doi:10.1016/j.eja.2010.12.001

Anderson MC, Hain C, Wardlow B, Pimstein A, Mecikalski JR, Kustas WP (2011) Evaluation of drought indices based on thermal remote sensing of evapotranspiration over the continental United States. J Clim 24:2025–2044. doi:10.1175/2010JCLI3812.1

Andreadis KM, Lettenmaier DP (2006) Trends in 20th century drought over the continental United States. Geophys. Res Lett 33. doi:10.1029/2006GL025711

De Wit AD, Van Diepen CA (2007) Crop model data assimilation with the ensemble Kalman filter for improving regional crop yield forecasts. Agric For Meteorol 146:38–56

Gemmer M, Becker S, Jiang T (2004) Observed monthly precipitation trends in China 1951–2002. Theor Appl Climatol 77:39–45. doi:10.1007/s00704-003-0018-3

He D, Wang J, Wang E (2015) Modelling the impact of climate variability and irrigation on winter canola yield and yield gap in Southwest China. MODSIM 2015, 21st International Congress on Modelling and Simulation. Modelling and Simulation Society of Australia and New Zealand, December 2015, pp. 389–395. http://www.mssanz.org.au/modsim2015/B3/he.pdf

He D, Wang J, Dai T, Feng L, Zhang J, Pan X, Pan Z (2014) Impact of climate change on maize potential productivity and the potential productivity gap in Southwest China. J Meteor Res 28:1155–1167. doi:10.1007/s13351-014-4047-x

Heim RR (2002) A review of twentieth-century drought indices used in the United States. Bull Am Meteorol Soc 83:1149–1165

Holzkämper A, Calanca P, Honti M, Fuhrer J (2015) Projecting climate change impacts on grain maize based on three different crop model approaches. Agric For Meteorol 214:219–230

Hou R, Ouyang Z, Li Y, Wilson GV, Li H (2012) Is the change of winter wheat yield under warming caused by shortened reproductive period? Ecol Evol 2:2999–3008. doi:10.1002/ece3.403

Huang B (1985) Agricultural productive potentiality-photosynthetic potential in China. Science Press, Beijing, China, pp. 15–22 in Chinese

Huo Z, Dai X, Feng S, Kang S, Huang G (2013) Effect of climate change on reference evapotranspiration and aridity index in arid region of China. J Hydrol 492:24–34. doi:10.1016/j.jhydrol.2013.04.011

Li Y, Ye W, Wang M, Yan X (2009) Climate change and drought: a risk assessment of crop-yield impacts. Clim Res 39:31–46. doi:10.3354/cr00797

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

Liu Y, Wang E, Yang X, Wang J (2010) Contributions of climatic and crop varietal changes to crop production in the North China Plain, since 1980s. Glob Chang Biol 16:2287–2299

Liu Z, Yang X, Hubbard KG, Lin X (2012) Maize potential yields and yield gaps in the changing climate of Northeast China. Glob Chang Biol 18:3441–3454. doi: 10.1111/j.1365-2486.2012.02774.x

Lu C, Fan L (2013) Winter wheat yield potentials and yield gaps in the North China Plain. Field Crop Res 143:98–105. doi:10.1016/j.fcr.2012.09.015

National Bureau of Statistics of China (2009) China statistical yearbook. China Statistics Press, Beijing in Chinese

Pandey DN, Gupta AK, Anderson DM (2003) Rainwater harvesting as an adaptation to climate change. Curr Sci 85:46–59

Porter JR, Gawith M (1999) Temperatures and the growth and development of wheat: a review. Eur J Agron 10:23–36. doi:10.1016/S1161-0301(98)00047-1

Qin Y, Liu J, Shi W, Tao F, Yan H (2013a) Spatial-temporal changes of cropland and climate potential productivity in northern China during 1990–2010. Food Secur 5:499–512. doi:10.1007/s12571-013-0280-x

Qin X, Weiner J, Qi L, Xiong Y, Li F (2013b) Allometric analysis of the effects of density on reproductive allocation and harvest index in 6 varieties of wheat (Triticum). Field Crop Res 144:162–166

Qiu J (2010) China drought highlights future climate threats. Nature 465:142–143. doi:10.1038/465142a

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

Thornthwaite CW (1948) An approach toward a rational classification of climate. Geogr Rev 38:55–94

Vicente-Serrano SM, Begueria S, López-Moreno JI (2010) A multiscalar drought index sensitive to global warming: the standardized precipitation evapotranspiration index. J Clim 23:1696–1718. doi:10.1175/2009JCLI2909.1

Wang L, Chen W, Zhou W, Huang G (2015a) Understanding and detecting super-extreme droughts in Southwest China through an integrated approach and index. Q J R Meteorol Soc 142:529–535

Wang T, Lu C, Yu B (2011) Production potential and yield gaps of summer maize in the Beijing-Tianjin-Hebei region. J Geogr Sci 21:677–688. doi:10.1007/s11442-011-0872-3

Wang J, Wang E, Feng L, Yin H, Yu W (2013) Phenological trends of winter wheat in response to varietal and temperature changes in the North China Plain. Field Crop Res 144:135–144. doi:10.1016/j.fcr.2012.12.020

Wang H, Wang P, Tian Y, Li W, Zeng Y (2012a) Assessment on meteorological factors of wheat growing period based on fuzzy evaluation method. J Agric 2:9–12

Wang N, Wang J, Wang E, Yu Q, Shi Y, He D (2015b) Increased uncertainty in simulated maize phenology with more frequent supra-optimal temperature under climate warming. Eur J Agron 71:19–33

Wang J, Wang E, Yang X, Zhang F, Yin H (2012b) Increased yield potential of wheat-maize cropping system in the North China Plain by climate change adaptation. Clim Chang 113:825–840. doi:10.1007/s10584-011-0385-1

Wang P, Zheng Y, He J, Zhang Q, Wang B (2007) Analysis of climate change from dry to wet phase in NW China with an aridity-wetness homogenized index. 2007 I.E. Int. Geosci. Remote Sens Symp 1778–1781. doi:10.1109/IGARSS.2007.4423165

Wu D, Yu Q, Lu C, Hengsdijk H (2006) Quantifying production potentials of winter wheat in the North China Plain. Eur J Agron 24:226–235. doi:10.1016/j.eja.2005.06.001

Yang X, Cheng C, Li Y (2010) Effect of cropland occupation and supplement on light-temperature potential productivity in China from 2000 to 2008. Chin Geogr Sci 20:536–544

Yu M, Li Q, Hayes MJ, Svoboda MD, Heim RR (2014) Are droughts becoming more frequent or severe in China based on the standardized precipitation evapotranspiration index: 1951–2010? Int J Climatol 34:545–558. doi:10.1002/joc.3701

Yuan B, Guo J, Ye M, Zhao J (2012) Variety distribution pattern and climatic potential productivity of spring maize in Northeast China under climate change. Chin Sci Bull 57:3497–3508. doi:10.1007/s11434-012-5135-x

You L, Rosegrant MW, Wood S, Sun D (2009) Impact of growing season temperature on wheat productivity in China. Agric For Meteorol 149:1009–1014. doi:10.1016/j.agrformet.2008.12.004

Zhang L, Xiao J, Li J, Wang K, Lei L, Guo H (2012) The 2010 spring drought reduced primary productivity in southwestern China. Environ Res Lett 7:045706. doi:10.1088/1748-9326/7/4/045706

Zhao H, Gao G, Yan X, Zhang Q, Hou M, Zhu Y, Tian Z (2012) Risk assessment of agricultural drought using the CERES-Wheat model: a case study of Henan Plain, China. Clim Res 50:247–256. doi:10.3354/cr01060