Combined Impact of Climate Change, Cultivar Shift, and Sowing Date on Spring Wheat Phenology in Northern China

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ABSTRACT

Distinct climate changes since the end of the 1980s have led to clear responses in crop phenology in many parts of the world. This study investigated the trends in the dates of spring wheat phenology in relation to mean temperature for different growth stages. It also analyzed the impacts of climate change, cultivar shift, and sowing date adjustments on phenological events/phases of spring wheat in northern China (NC). The results showed that significant changes have occurred in spring wheat phenology in NC due to climate warming in the past 30 years. Specifically, the dates of anthesis and maturity of spring wheat advanced on average by 1.8 and 1.7 day $(10\ \mathrm{yr})^{-1}$. Moreover, while the vegetative growth period (VGP) shortened at most stations, the reproductive growth period (RGP) prolonged slightly at half of the investigated stations. As a result, the whole growth period (WGP) of spring wheat shortened at most stations. The findings from the Agricultural Production Systems Simulator (APSIM)-Wheat model simulated results for six representative stations further suggested that temperature rise generally shortened the spring wheat growth period in NC. Although the warming trend shortened the lengths of VGP, RGP, and WGP, the shift of new cultivars with high accumulated temperature requirements, to some extent, mitigated and adapted to the ongoing climate change. Furthermore, shifts in sowing date exerted significant impacts on the phenology of spring wheat. Generally, an advanced sowing date was able to lower the rise in mean temperature during the different growth stages (i.e., VGP, RGP, and WGP) of spring wheat. As a result, the lengths of the growth stages should be prolonged. Both measures (cultivar shift and sowing date adjustments) could be vital adaptation strategies of spring wheat to a warming climate, with potentially beneficial effects in terms of productivity.

Key words: adaptation, climate warming, sowing date, spring wheat, growth stages, northern China

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1. Introduction

A warming climate is an accepted phenomenon under global change, and one that is projected to accelerate in the near future (Zhang Li et al., 2012; IPCC, 2013). Climate change in China is consistent with global climate change (Ding et al., 2006), wherein the amplitude of the increase in mean annual temperature is highest in northern China (NC) (Yang et al., 2011). A warming climate has significant impacts on human life, including agricultural production for human consumption (Porter and Semenov, 2005; Lobell and Field, 2007; Tan et al., 2015; Zhang H. L. et al., 2015).

Phenology encompasses plant growth processes largely driven by meteorological conditions (Menzel et al., 2006; Wang et al., 2013). Thus, phenological changes are strong indicators for changes in climate and environmental conditions (van Bussel et al., 2011;

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Diskin et al., 2012; He et al., 2015). Crops exhibit known observed responses to weather and climate that can strongly influence crop growth and development (Tao et al., 2006; Challinor et al., 2009; Xiao et al., 2013). Research on global warming suggests a close connection between crop phenology and climate variability/change (Chmielewski et al., 2004). For instance, in Germany, the phenology of 78 agricultural and horticultural events during 1951–2004 occurred significantly earlier than 53 years ago (Estrella et al., 2007). In Romania, Croitoru et al. (2012) documented that the increasing temperature trend has resulted in earlier occurrences of anthesis and maturity of winter wheat for many regions in the country. In China, significant warming trends in seasonal temperature have shifted crop [such as winter wheat (Xiao et al., 2013; He et al., 2015), rice (Zhang et al., 2013), maize (Li et al., 2014; Xiao et al., 2016), and cotton (Wang et al., 2008)] phenology across China during the past several decades.

To a large extent, crop yield is determined by the length and time of various phenological stages/phases (Jamieson et al., 1998). Generally, high temperature shortens the length of crop growth seasons and thereby limits the interception of radiation. Thus, global warming trends are projected to reduce grain yield through accelerated phenological development (Porter and Gawith, 1999; Ludwig and Asseng, 2010; Asseng et al., 2011). However, crop phenology can be confounded by the effects of weather/climate conditions and agronomic factors such as cropping systems, cultivar choices, sowing dates (SDs), and soil conditions (Tao et al., 2012; Xiao et al., 2013; Zhang Jingting et al., 2015).

Spring wheat is a staple crop cultivated in NC (E et al., 2013). Changes in spring wheat phenology can be readily observable and directly monitored in conventional field experiments. Phenological changes in the past several decades can therefore be used to determine the response of spring wheat to climate change and adjustments in SD in terms of growth and development (Zhao et al. 2009). In this study, phenological phases of spring wheat were analyzed for the period 1981–2009 by using field data collected from 18 agrometeorological experimental stations across NC. Furthermore, The Agricultural Production Systems Simulator (APSIM)-Wheat model was used to separate the effects of climate change, cultivar shift, and field management adjustment (in this study, mainly referring to the shift in SD) on spring wheat phenology in the study area. Thus, the main objectives of this study are to: (1) analyze the trends in spring wheat phenology for the last three decades in NC; and (2) determine the relatedness of the trends in spring wheat phenology with climate change, cultivar shift, and SD in this study area. The results of the study will not only deepen current insights into the impact of climate change on crop production, but also enhance the adoption of agronomy practices capable of helping us to adapt to the warming and variability of climatic conditions.

2. Data and methods

2.1 Study area and data

In this study, data on spring wheat phenology were collected from 18 national agrometeorological experimental stations for the period 1981–2009. The stations, operated by the China Meteorological Administration (CMA) and provincial meteorological administrations (Tao et al., 2014), are fairly distributed across the main spring wheat cultivation regions of NC (Fig. 1). These include: Hebei (HB), Gansu (GS), and Qinghai (QH) provinces; and Ningxia (NX), Xinjiang (XJ), and Inner Mongolia (IMG) regions (Fig. 1). Agro-technicians at the stations were enlisted to record the dates of the main phenological stages/phases of spring wheat during the growing season. This included the dates of sowing, emergence, heading, anthesis, and maturity.

Daily weather data for 1980–2009 were from a total of 756 ground-monitoring meteorological stations across the country. Of the 756 stations, 11 were at the same locations as agrometeorological stations. There were no nearby weather stations for 7 of 18 agrometeorological stations. For these 7 stations, daily weather data were estimated by using the method of Thornton et al. (1997), i.e., by interpolating data from the 756

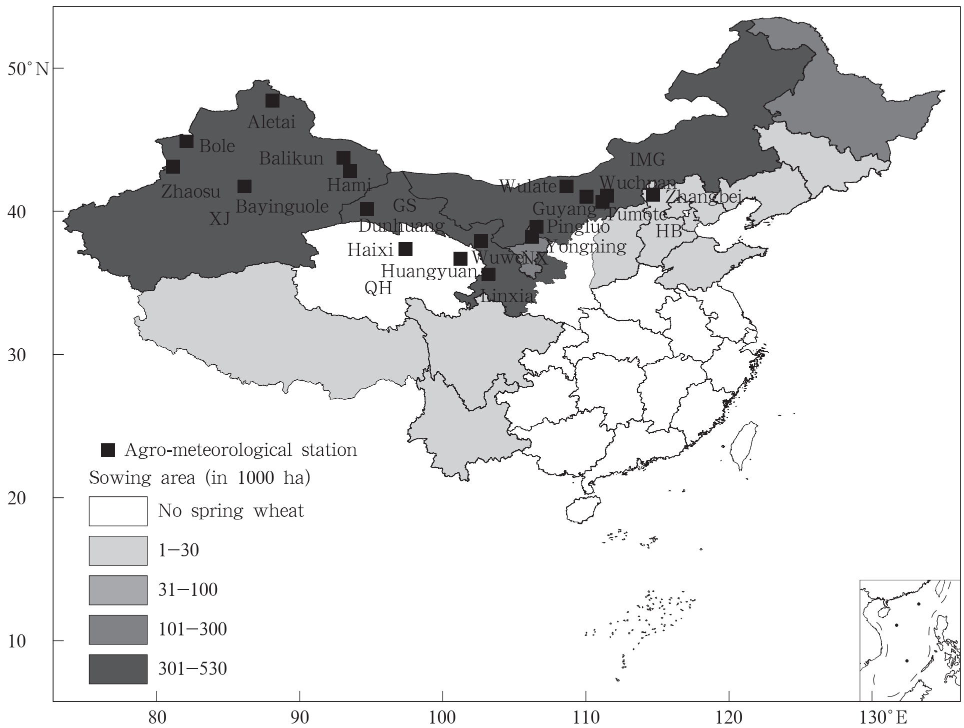

Fig. 1. Map of China depicting the locations of the agrometeorological experimental stations where data were collected for the study. The representative stations are Guyang, Zhangbei, Pingluo, Wuwei, Haixi, and Hami stations, where historical daily weather data were collected to run the APSIM model.

weather stations at a resolution of approximately 10 km. By using the method, daily average temperature was derived for each of the agrometeorological experimental stations for the period 1981–2009 (Xiao et al., 2013). Furthermore, historical daily weather data (including minimum and maximum temperature, sunshine duration, and precipitation) used in APSIM for six representative stations were also obtained from the CMA. Solar radiation for the six stations was derived from observed sunshine hours using the Ångström–Prescott equation (Ångström, 1924; Prescott, 1940).

2.2 Methods

Firstly, the mean of the field-observed temperature ($T_{\rm mean}$) for the three growth stages from sowing to anthesis (vegetative growth period, VGP), anthesis to maturity (reproductive growth period, RGP), and sowing to maturity (whole growth period, WGP), were calculated based on the observed sowing, anthesis, and maturity dates at each station. Next, the mean dates of sowing, anthesis, and maturity of winter wheat for the period 1980–2009 were computed for each station. Then, based on the mean phenological dates, the mean temperature ($T'_{\rm mean}$) for the three growth stages (VGP, RGP, and WGP) were separately computed for each of the stations. Moreover, accumulated temperature (AT, the sum of daily temperature > 0°C) during the three growth periods (VGP, RGP, and WGP) was calculated based on the observed phenological date. By using regression analysis (Challinor et al., 2009), the trends in the phenological phases of spring wheat, the durations of the growth stages, and $T_{\rm mean}$, $T'_{\rm mean}$, and AT were calculated for each station for the period 1981–2009. The time-variant trend of each variable was determined by using the linear regression model

$$Y_i = kX_i + b, \qquad (1)$$

where Y_i is the observed phenological date/phase ($T_{\rm mean}$, $T'_{\rm mean}$, or AT) in year i; k is the linear regression slope; b is the slope intercept; and X_i is year i (i=1, 2, 3, ..., 29). Bivariate correlation analysis was performed to determine the correlation between the duration of each of the three growth stages (VGP, RGP, and WGP) and corresponding T_{mean}. Then, the statistical significance of the results was determined with the two-tailed t-test analysis (Challinor et al., 2009).

Generally, the observed phenological events (M_{observed}) were mainly impacted by climate change, cultivar shift, and SD adjustments. With the APSIM-Wheat model, two experiments (M1 and M2) were set up to determine the effects of climate change, cultivar shift, and SD adjustments on phenological processes and growth period duration of spring wheat. A total of six representative stations (Guyang in IMG, Zhangbei in HB, Pingluo in NX, Wuwei in GS, Haixi in QH, and Hami in XJ) were used for this purpose (Fig. 1). Under experiment M1, SD was set to the average observed SDs for 1981–2009. This allowed for the detection of the trends in phenological events as influenced by climate change under experiment M1. In experiment M2, the input SD was the observed SDs for 1981–2009. Here, it was possible to determine the trends in phenological events as influenced by the combined effects of climate change and SD adjustments in the study area. Thus, the impacts of cultivar shift or SD on spring wheat phenology were determined via linear regression analysis as in Eq. (1). Here, $Y_i = M_{\text{observed}} - \text{M2}_i$ (for the impact of cultivar shift), or $Y_i = \text{M2}_i - \text{M1}_i$ (for the impact of SD), in which M_{observed}, M1_i, and M2_i are the values of each variable in year i, respectively, under observed phenological events, in experiments M1 and M2.

2.3 APSIM-Wheat model

APSIM version 7.4 was used in this study. APSIM is a cropping system model developed by the Agricultural Production Systems Research Unit of Australia. APSIM is a component-driven model that concurrently runs several modules, including crop growth/development and soil water/nitrogen dynamics (Keating et al., 2003). APSIM simulates phenological processes, biomass accumulation and partitioning, and leaf area index, as well as root, stem, leaf, and grain growths in daily time-steps from sowing to maturity. In its genetic crop module, APSIM uses genetic coefficients related to the duration of each growth phase, photoperiod sensitivity, grain size, and grain-filling rate. A detailed description of APSIM and its crop/soil modules is documented in Keating et al. (2003). APSIM requires daily weather data as an input, including solar radiation, maximum and minimum air temperature, and precipitation.

The APSIM-Wheat model was calibrated and validated by using data from the six representative stations. To do this, the most typical cultivated cultivar at each of the stations during 1981–85 was identified. Then, observed data for 1981–83 were used to calibrate the genetic parameters of the APSIM-Wheat model. Also, observed data for 1984–85 for each given cultivar were used to validate the model for the respective cultivars. Finally, the validated model was run on historical weather data for 1981–2009 to simulate station-based dates of anthesis and maturity.

Overall, the model-simulated and field-observed dates of anthesis and maturity agreed closely for the six representative stations (Fig. 2). The differences between the simulated and observed dates of anthesis and maturity amounted to less than 5 days, suggesting that the APSIM-Wheat model performed fairly well in simulating spring wheat phenology in the study area.

3. Results

3.1 Trends in phenology and accumulated temperature for spring wheat during 1981–2009

In NC, spring wheat is generally sown from early March [DOY 60 (DOY: day of year)] to late April (DOY 115). Anthesis generally occurs from late May (DOY 145) to mid-July (DOY 197), and maturity is generally from late June (DOY 178) to early September (DOY 245) (Fig. 3). As shown in Fig. 3, the periods from sowing to anthesis (VGP), anthesis to maturity (RGP), and sowing to maturity (WGP) were 63–109, 29–53, and 98–157 days, respectively. This result showed clear spatial patterns in the lengths of the growth stage periods across the investigated stations due to the different climatic and environmental conditions.

As shown in Table 1, the SD of spring wheat during 1981–2009 became delayed at 9 of the 18 investiga-

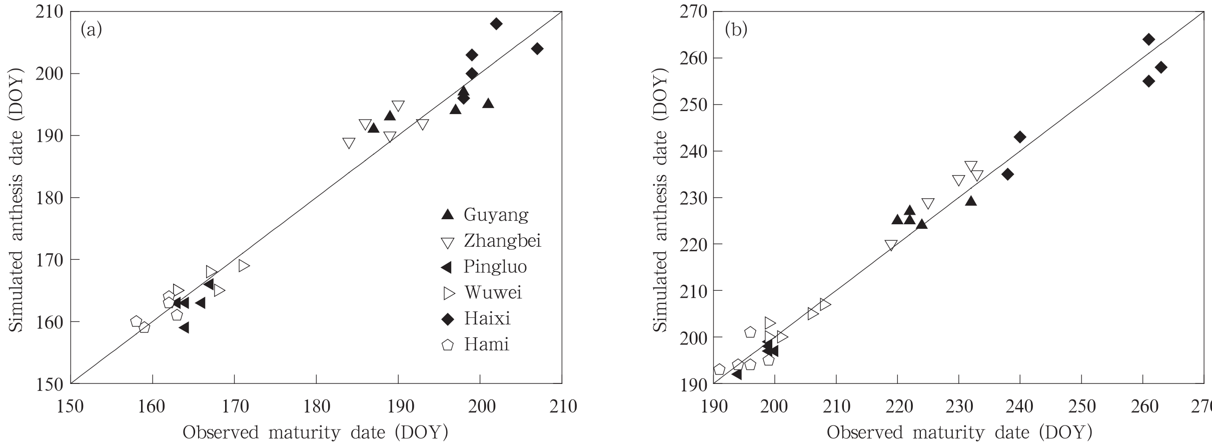

Fig. 2. Results of the APSIM-Wheat model validation analysis for the dates (DOY: day of year) of anthesis and maturity at different stations in the study area.

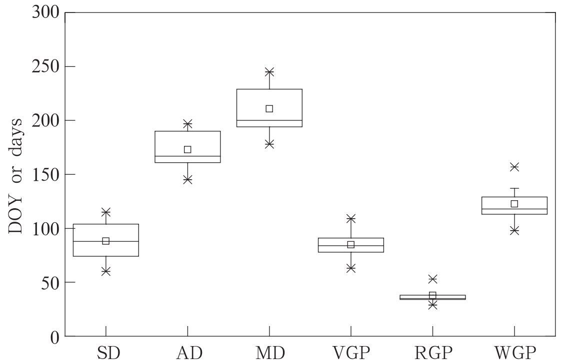

Fig. 3. Characteristics of spring wheat phenology for the period 1981–2009 at the investigated stations in NC. SD: sowing date, AD: anthesis date, MD: maturity date; VGP: duration from sowing to anthesis; RGP: duration from anthesis to maturity; WGP: duration from sowing to maturity.

ted stations, with a significant trend at 5 of the stations ($p < 0.05$). The SD, however, advanced at 9 stations (mainly in Ningxia and Xinjiang), with a significant trend at 3 stations (including Pingluo, Bayinguole, and Hami) ($p < 0.01$). The AD and MD were largely driven by temperature. As shown in Table 1, the date of anthesis (AD) advanced at 15 stations, with significant trends at 11 stations ($p < 0.05$). Similar to AD, most of the stations experienced early maturity of spring wheat (Table 1).

The advance or delay in phenology induced corresponding changes in the durations of the different growth stages of spring wheat. As shown in Table 1, VGP shortened at 14 of the 18 investigated stations, and was statistically significant at 9 of these stations ($p < 0.05$). Also, RGP shortened at 9 stations, with a significant trend ($p < 0.05$) at only 2 stations (Bole and Aletai). In contrast, RGP lengthened slightly at 9 stations. Among these stations, 3 stations (Yongning, Dunhuang, and Hami) had significant trends at $p < 0.05$ (Table 1). As shown in Table 1, WGP shortened at most of the stations, and was significant at 8 stations. For all the investigated stations, the SD delayed on average by 0.3 day (10 yr)$^{-1}$. In contrast, the AD and subsequent MD advanced on average by 1.8 and 1.7 day (10 yr)$^{-1}$, respectively (Fig. 4). As shown in Fig. 4, VGP and WGP shortened on average by 2.1 and 1.9 day (10 yr)$^{-1}$, respectively. However, RGP advanced slightly on average by 0.2 day (10 yr)$^{-1}$.

As shown in Table 2, AT during VGP increased at 12 of the 18 investigated stations, with significant trends at 5 stations ($p < 0.05$). AT during RGP increased significantly at 9 stations, but decreased significantly at Bole station (Table 2). As a result, AT during WGP increased at all stations except Bayinguole, Bole, and Aletai. All these results indicate that cultivar shift had significant impacts on the phenology of spring wheat during 1981–2009.

Table 1. Trends in spring wheat phenology (unit: day (10 yr)$^{-1}$) for the period 1981–2009 at the investigated stations in NC

Province	Station	SD	AD	MD	VGP	RGP	WGP
IMG	Wulate	–1.9	–1.5*	–0.4	0.4	1.1	1.5
	Wuchuan	2.5*	–0.1	–0.7	–2.6*	–0.6	–3.2*
	Guyang	5.5**	3.3**	3.0	–2.2	–0.3	–2.5
	Tumote	2.5**	–1.7	–0.9	–4.2**	0.8	–3.4**
HB	Zhangbei	5.9**	1.8	1.4	–4.0*	–0.4	–4.5*
NX	Pingluo	–5.9**	–3.5**	–3.7**	2.4	–0.2	2.2
	Yongning	–1.9	–3.6**	–1.6	–1.8	2.0**	0.3
GS	Lixia	0.3	–2.3*	–3.8**	–2.6*	–1.5	–4.1**
	Wuwei	0.8	–4.0**	–3.6**	–4.8**	0.4	–4.4**
	Dunhuang	–1.3	–4.0**	–2.4*	–2.7*	1.6*	–1.1
QH	Huangyuan	2.4	1.4	3.0	–1.0	1.7	0.6
	Haixi	8.0**	–0.1	–0.6	–8.1**	–0.5	–8.6**
XJ	Bayinguole	–6.3**	–3.1**	–4.4**	3.3	–1.3	1.9
	Hami	–3.8**	–3.3**	–2.0	0.5	1.3*	1.8
	Zhaosu	–1.4	–5.2**	–3.3	–3.8*	1.9	–1.9
	Balikun	–0.8	–2.9**	–1.3	–2.2	1.6	–0.6
	Bole	–2.0	–3.3**	–5.8**	–1.3	–2.4**	–3.7*
	Aletai	2.4	–0.9	–2.7*	–3.3*	–1.8*	–5.1*

Note: A single asterisk (*) denotes a significant trend at the 5% significance level; a double asterisk (**) denotes a significant trend at the 1% significance level.

3.2 Correlation of the observed duration of different growth stages with mean temperature and SD

For all the investigated stations, the duration of the three growth stages (VGP, RGP, and WGP) was negatively correlated with the corresponding mean temperature ($T_{\rm mean}$) (Fig. 5). However, the correlation coefficients for VGP and WGP were higher than that for RGP (Fig. 5). As depicted in Fig. 6a, the duration of VGP was significantly correlated with $T_{\rm mean}$. Also, the duration of RGP shortened with rising $T_{\rm mean}$ ($T_{\rm mean}$ < 23℃; Fig. 6b). The results suggest that a warming climate could accelerate phenological development and thereby shorten the spring wheat growth period in NC.

The downward slope of the trend line is a clear reflection of the negative impacts of delayed SD on the duration of VGP and WGP (Figs. 7a and 7c). Across the investigated stations, however, adjustments in SD had no significant and consistent impact on the duration of RGP in NC (Fig. 7b).

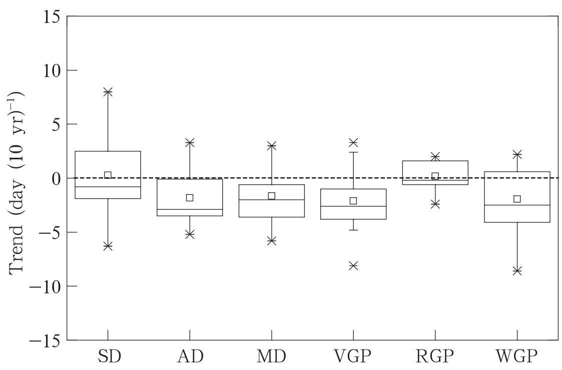

Fig. 4. Trends in spring wheat phenology in NC for the period 1981–2009 at 18 investigated stations across the region.

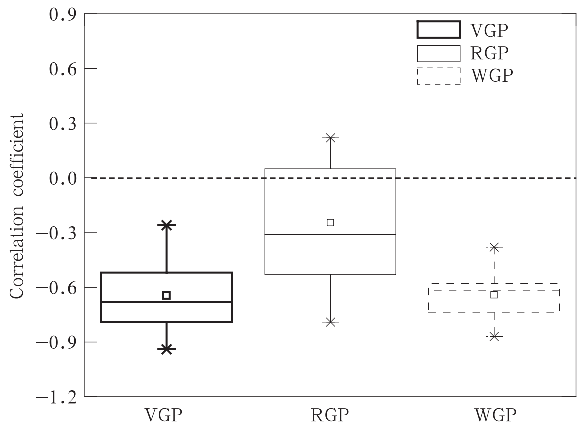

Fig. 5. Correlation between duration of the three growth stages (VGP, RGP, and WGP) and the corresponding $T_{\rm mean}$.

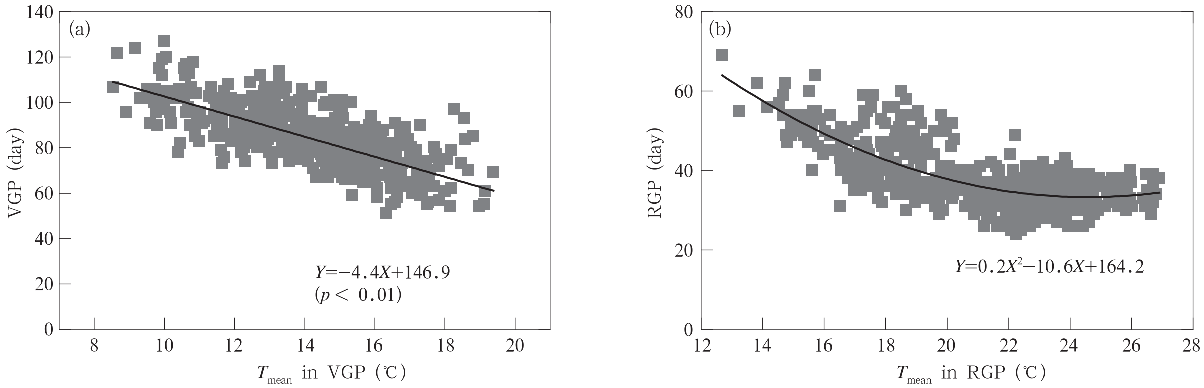

Fig. 6. Correlation between (a) duration of spring wheat VGP versus $T_{\rm mean}$ for the period from sowing to anthesis and (b) duration of spring wheat RGP versus $T_{\rm mean}$ for the period from anthesis to maturity in NC.

Table 2. Trends in accumulated temperature (AT) of spring wheat during three growth stages for the period 1981–2009 at the investigated stations in NC

Province	Station	AT_{VGP} (℃ yr^{-1})	AT_{RGP} (℃ yr^{-1})	AT_{WGP} (℃ yr^{-1})
IMG	Wulate	2.4	4.5**	7.0**
	Wuchuan	3.5	0.9	4.4*
	Guyang	7.5*	–1.0	6.5**
	Tumote	–1.3	4.1*	2.8**
HB	Zhangbei	2.5	0.1	2.6
NX	Pingluo	1.5	0.9	2.4
	Yongning	2.5	7.8**	10.3**
GS	Lixia	3.2*	–0.6	2.6
	Wuwei	0.5	3.7**	4.2**
	Dunhuang	–1.5	6.3**	4.7*
QH	Huangyuan	6.0**	5.2**	11.2**
	Haixi	4.6*	1.0	5.6**
XJ	Bayinguole	–0.4	–1.3	–1.7
	Hami	–0.8	4.7**	3.9
	Zhaosu	–1.9	3.7*	1.8
	Balikun	2.8*	8.0**	10.7**
	Bole	–0.8	–5.7*	–6.5*
	Aletai	0.7	–3.1	–2.4

Note: A single asterisk (*) denotes a significant trend at the 5% level; a double asterisk (**) denotes a significant trend at the 1% level; AT_{VGP}, accumulated temperature in the VGP; AT_{RGP}, accumulated temperature in the RGP; AT_{WGP}, accumulated temperature in the WGP.

3.3 Impacts of climate change, cultivar shift and sowing date adjustment on spring wheat phenology

For the six representative stations, the trends in SD became delayed by 0.8–8.0 day (10 yr)$^{-1}$ at Wuwei, Guyang, Haixi, and Zhangbei stations. On the contrary, the trends in SD at Pingluo and Hami stations advanced by 5.9 and 3.8 day (10 yr)$^{-1}$, respectively (Table 3). This suggests that the observed changes in spring wheat phenology, to some extent, were driven by adjustments in SD.

For the M1 experiment (Table 3), climate change caused AD of spring wheat to advance by 1.6–3.9 day (10 yr)$^{-1}$ in the study area. Similarly, MD advanced by 1.0–6.0 day (10 yr)$^{-1}$ at all of the six representative stations. Due to climate-driven changes in phenology trends, winter wheat VGP and WGP shortened significantly by 1.6–3.9 and 1.0–6.0 day (10 yr)$^{-1}$, respectively. Moreover, RGP shortened significantly at Wuwei, Haixi, and Zhangbei stations, whereas it lengthened significantly at Hami (Table 3).

From the comparison of $M_{\rm observed}$ and M2, cultivar shift during 1981–2009 significantly delayed anthesis at Guyang and Haixi stations by 3.0 and 1.6 day (10 yr)$^{-1}$, respectively. Due to the cultivar shift, the spring wheat MD delayed at all of the representative stations, and the trend was significant at Wuwei, Guyang, Haixi, and Zhangbei stations (Table 3). Furthermore, cultivar shift mainly prolonged the length of VGP and RGP at most of the representative stations. As shown in Table 3, cultivar shift in the past three decades also prolonged the WGP of spring wheat at all of the six representative stations, with significant trends at Wuwei, Guyang, Haixi, and Zhangbei stations.

Furthermore, different trends in SD had different impacts on spring wheat phenology. The trends obtained from M2 minus M1 reflected the impacts of SD adjustments on spring wheat phenology (Table 3). Al-

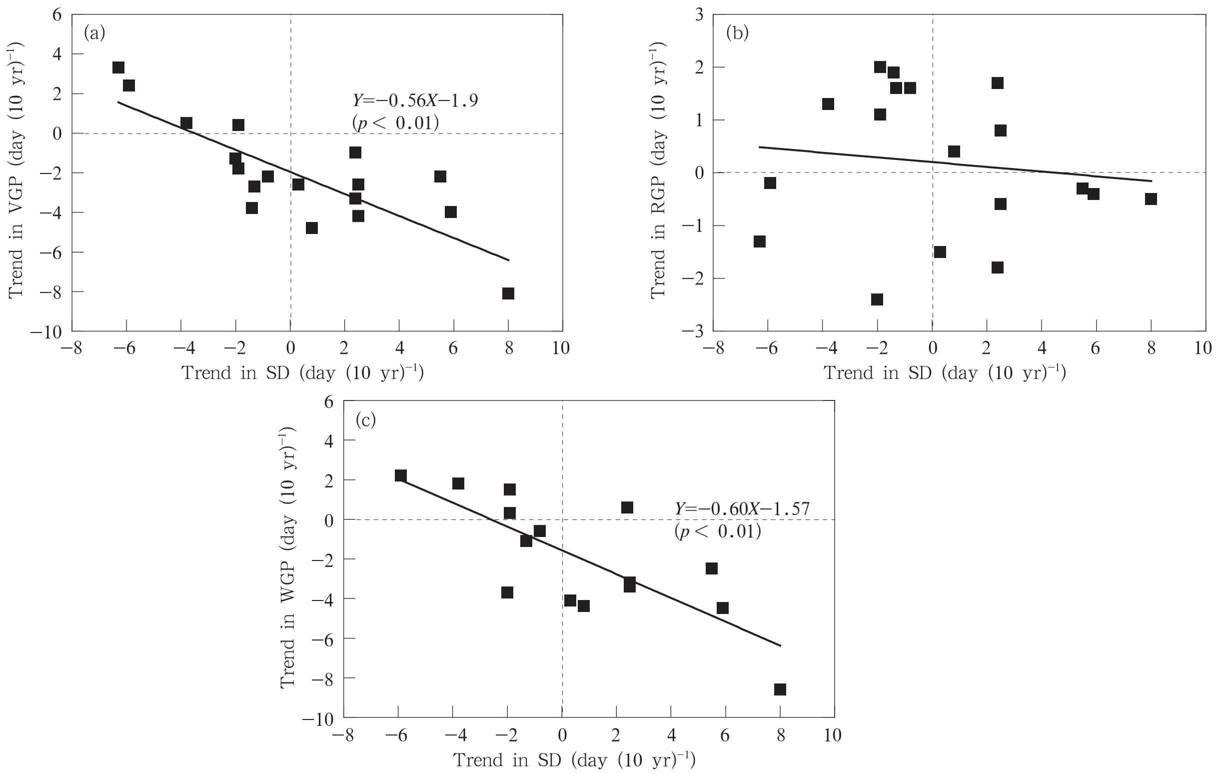

Fig. 7. Correlations between trends in (a) VGP and SD, (b) RGP and SD, and (c) WGP and SD, of spring wheat in NC.

though delayed SD apparently delayed AD and MD, the numbers of days by which AD and MD became delayed were less than for SD (Table 3). While AD and MD advanced with advancing SD, the numbers of days by which AD and MD advanced were less than for SD (Table 3). Thus, with a delayed SD of spring wheat, the VGP and WGP periods shortened. Also, with an advanced SD of spring wheat, the VGP and WGP periods lengthened. However, the SD of spring wheat only had a slightly insignificant effect on RGP (Table 3).

4. Discussion

4.1 Climate change and wheat phenology

Climate variability influences crop phenological processes in various ways, including shifts in phenological dates and in the durations of phenological periods (Tao et al., 2006; Xiao et al., 2013). Generally, observed changes in crop phenological phases or growth stages are tied to changes in temperature (Estrella et al., 2007; Xiao et al., 2015). This study shows increasing $T'_{\rm mean}$ of three different growth stages (VGP, RGP, and WGP) at 0.67, 0.61, and 0.65°C (10 yr)$^{-1}$, respectively (Fig. 8). However, the calculated actual $T_{\rm mean}$ based on field-observed data for the three growth stages (VGP, RGP, and WGP) had greater ranges of variation due to phenological changes (Fig. 8). The results suggest that crop phenological trends are influenced by climatic conditions during growth processes. Overall, the temperature increase in the past several decades changed the phenological processes of spring wheat. Correlation analysis between the durations of the various growth stages of spring wheat and the corresponding mean temperatures (Xiao et al., 2015) showed significant negative correlations. This suggests that a temperature rise generally shortens growth periods of spring wheat in NC (Zhao et al., 2009).

4.2 Cultivar shift and wheat phenology

During the past several decades, there were frequ-

Table 3. Observed and simulated trends (in day (10 yr)$^{-1}$) in SD, AD, and MD along with the durations of VGP, RGP, and WGP of spring wheat at six representative stations in NC for the period 1981–2009

	Station	Wuwei	Guyang	Pingluo	Haixi	Zhangbei	Hami
SD	Mean (DOY)	78	111	65	89	115	79
	Observed trend	0.8	5.5**	–5.9**	8.0**	5.9**	–3.8**
AD	Observed trend	–4.0**	3.3*	–3.5**	–0.1	1.8	–3.3**
	Trend in M1	–3.9**	–1.9**	–3.3**	–3.9**	–2.1**	–1.6*
	Trend in M2	–3.8**	0.3	–4.1**	–1.7*	0.8	–3.2**
	Trend in M2–M1	0.2	2.1**	–0.4	2.3**	2.9**	–1.6**
	Trend in $M_{\rm observed}$–M2	–0.2	3.0*	0.6	1.6*	1.0	–0.1
MD	Observed trend	–3.6**	3.0	–3.7**	–0.6	1.4	–2.0
	Trend in M1	–4.7**	–2.4**	–3.3**	–6.0**	–3.4**	–1.1*
	Trend in M2	–4.8**	0.1	–4.3**	–3.3*	–0.5	–2.6**
	Trend in M2–M1	0.1	2.3**	–0.7	2.7**	3.0**	–1.6**
	Trend in $M_{\rm observed}$–M2	1.2*	2.9*	0.6	2.7*	1.9*	0.6
VGP	Observed trend	–4.8**	–2.2	2.4	–8.1**	–4.0*	0.5
	Trend in M1	–3.9**	–1.9**	–3.3**	–3.9**	–2.1**	–1.6*
	Trend in M2	–4.5**	–5.3**	1.8	–9.7**	–5.1**	0.6
	Trend in M2–M1	–0.5	–3.4**	5.5**	–5.8**	–3.0**	2.3**
	Trend in $M_{\rm observed}$–M2	–0.3	3.1*	0.6	1.6*	1.1	–0.1
RGP	Observed trend	0.4	–0.3	–0.2	–0.5	–0.4	1.3*
	Trend in M1	–0.8*	–0.5	0.1	–2.1**	–1.3**	0.5*
	Trend in M2	–1.0*	–0.2	–0.2	–1.7*	–1.2*	0.6
	Trend in M2–M1	–0.2	0.2	–0.3	0.4	0.1	0.1
	Trend in $M_{\rm observed}$–M2	1.4*	–0.1	0.0	1.2*	0.8	0.7
WGP	Observed trend	–4.4**	–2.5	2.2	–8.6**	–4.5*	1.8
	Trend in M1	–4.7**	–2.4**	–3.3**	–6.0**	–3.4**	–1.1*
	Trend in M2	–5.6**	–5.4**	1.6	–11.4**	–6.3**	1.2
	Trend in M2–M1	–0.8	–3.2**	5.3**	–5.4**	–2.8**	2.2**
	Trend in $M_{\rm observed}$–M2	1.2*	2.9*	0.6	2.8*	1.8*	0.6

Note: A single asterisk (*) denotes a significant trend at the 5% level; a double asterisk (**) denotes a significant trend at the 1% level.

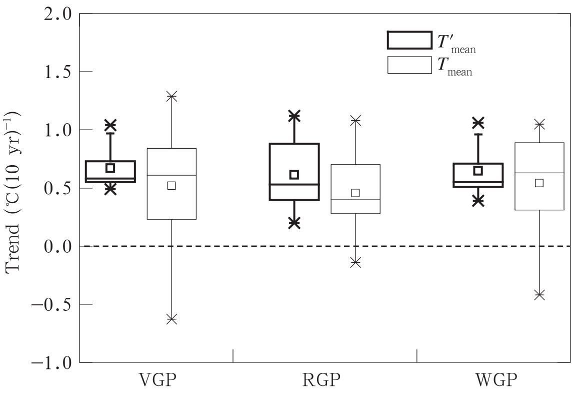

Fig. 8. Trends in mean temperature derived from the average growth period ($T'_{\rm mean}$) and field-observed growth period ($T_{\rm mean}$) during different growth periods at the investigated stations.

ent changes in cultivars sowed in the study area (Tao et al., 2012). We further illustrated changes in cultivar AT of spring wheat for all the investigated stations. Due to the cultivar shift, AT during the three different growth stages (VGP, RGP, and WGP) showed increased trends at most of the investigated stations. All these results indicate that the thermal requirement of cultivars from sowing to anthesis, from anthesis to maturity, and from sowing to maturity, all increased at most stations. As a result, cultivar shift during 1981–2009 mainly prolonged the length of VGP, RGP, and WGP at most representative stations. To a large extent, wheat yield is determined by the length of the various growth phase. Although the warming trend shortened the durations of VGP, RGP, and WGP, the shift of new cultivars with high AT requirements, to some extent, mitigated and adapted to the ongoing climate change (Xiao et al., 2013). Therefore, our findings have important implications in so far as new wheat cultivars with higher thermal requirements and longer growth stages should be adopted in the study area to take advantage of the increased heat resource from climate warming (Tao et al., 2012).

4.3 Sowing date and wheat phenology

Sowing depends not only on weather/climate conditions, but also on other factors such as soil water content and farm management practices. Changes in SD had a significant effect on T_{mean} of spring wheat growth periods (Fig. 9), especially VGP and WGP. In the past several decades, delayed SDs significantly increased T_{mean} for VGP and WGP. However, for advanced SDs exceeding 4 days, T_{mean} for VGP and WGP decreased (Figs. 9a and 9c).

Thus, to some extent, shifts in SD of spring wheat change the weather conditions in spring wheat fields (E et al., 2013). Also, and again to a certain extent, advanced SDs slowed down the rise in T_{mean} of spring wheat growth stages. The study found that when SD advancement reached 4 day (10 yr)$^{-1}$, T_{mean} of VGP and WGP decreased under warming climatic conditions. Thus, to some extent, changes in SD influence the durations of wheat growth stages (Semenov, 2009; White et al., 2011; Zhang Kai et al., 2012). This study reveals that, an early SD can mitigate the negative effects of warming climatic conditions on VGP and WGP of spring wheat in NC. This is probably because advancements in SDs lengthen the vegetative period of spring wheat.

5. Conclusions

This study focused on the spatial and temporal characteristics of the change in phenology of spring wheat in NC in the past three decades. The analysis shows significant changes in spring wheat phenology in the past 30 years under global climate change. Changes in phenological dates inevitably changed the durations of various growth stages of spring wheat. Although the warming trend shortened the lengths of VGP, RGP, and WGP, the shift of new cultivars with high AT requirements, to some extent, mitigated and adapted to the ongoing climate change. SDs at different stations had different trends of change. Where SD

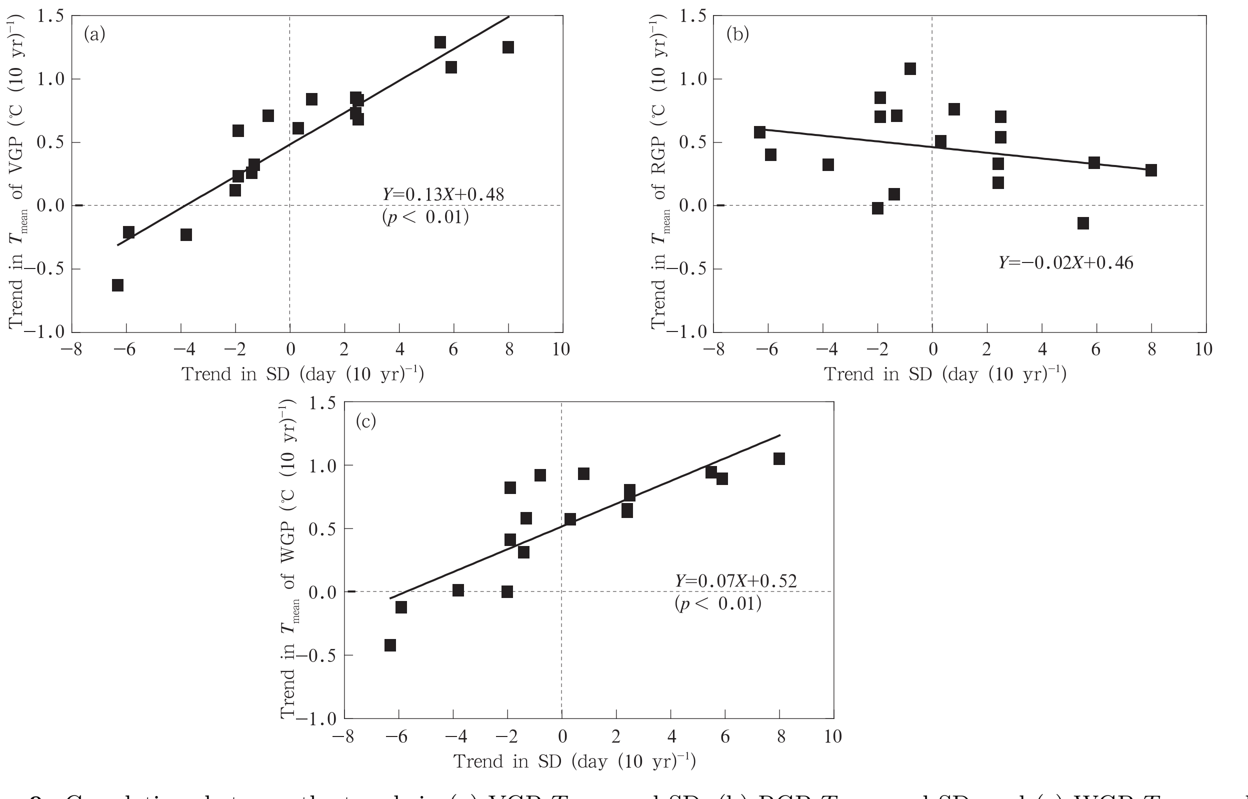

Fig. 9. Correlations between the trends in (a) VGP T_{mean} and SD, (b) RGP T_{mean} and SD, and (c) WGP T_{mean} and SD, of spring wheat in NC.

delayed, both VGP and WGP shortened, and vice-versa. However, the spring wheat SD had only a slightly insignificant effect on RGP. The findings of this study could be useful in developing strategies to mitigate the impact of climate change on wheat production, as well as to strengthen food security and promote social stability.

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