

Effects of changing climate and cultivar on the phenology and yield of winter wheat in the North China Plain

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Abstract Understanding how changing climate and cultivars influence crop phenology and potential yield is essential for crop adaptation to future climate change. In this study, crop and daily weather data collected from six sites across the North China Plain were used to drive a crop model to analyze the impacts of climate change and cultivar development on the phenology and production of winter wheat from 1981 to 2005. Results showed that both the growth period (GP) and the vegetative growth period (VGP) decreased during the study period, whereas changes in the reproductive growth period (RGP) either increased slightly or had no significant trend. Although new cultivars could prolong the winter wheat phenology (0.3–3.8 days per decade for GP), climate warming impacts were more significant and mainly accounted for the changes. The harvest index and kernel number per stem weight have significantly increased. Model simulation indicated that the yield of winter wheat exhibited increases (5.0–19.4 %) if new cultivars were applied. Climate change demonstrated a negative effect on winter wheat yield as suggested by the simulation driven by climate data only (–3.3 to –54.8 kg ha⁻¹ year⁻¹, except for Lushi). Results of this study also indicated that winter wheat cultivar development can compensate for the negative effects of future climatic change.

Keywords Winter wheat · Climate change · Cultivar · Phenology · Potential yield · APSIM model

Introduction

Wheat is the world's most widely grown food crop which provides one fifth of the global calorie consumption (Reynolds et al. 2011; FAO 2013). China is the largest wheat producer and consumer in the world, and wheat is China's third leading production crop. In 2010, China produced 17.6 % (115 million metric tons) of the world's wheat on 11.2 % (24 million hectares) of the world's wheat harvest area (FAO 2013). The North China Plain (NCP) is the largest wheat-producing region in China and accounts for 50 % of the nation's wheat grain production (National Bureau of Statistics of China 2012). This region implements irrigation extensively and has an intensive wheat-maize double-cropping system (Zhou et al. 2007a; Liu et al. 2010).

Historical climate data during 1961–2003 indicated that the NCP was becoming warmer, drier, and dimmer (Che et al. 2005; Liu et al. 2005; Ren et al. 2008; Fu et al. 2009; Chen et al. 2013). The Intergovernmental Panel on Climate Change (IPCC 2007) published a report with similar conclusions regarding an ongoing global warming trend. Observations from 1958 to 1998 in the NCP showed that the daily mean temperatures, daily maximum temperatures, and daily minimum temperatures had increased by 0.83, 0.18, and 1.46 °C, respectively (Fu et al. 2009). Ding et al. (2006) noted that these three daily temperatures changed rapidly from 1980 to 1998 and projected the potential increasing in future temperatures. Winter warming should be taken more attention, as its temperatures are increasing at a rate that is approximately four times more rapid than the summer warming rate (Piao et al. 2010). From 1958 to 1998, the annual precipitation in the NCP

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decreased by approximately 43.9 mm or 6.7 % (Fu et al. 2009). Although human activity is not the primary source of atmospheric aerosols, actions such as burning of carbon-based materials, whether for clearing land or for fuel, have resulted in a significant decrease in solar radiation in the NCP (Che et al. 2005; Liang and Xia 2005; Qian et al. 2006; Shi et al. 2008; Chen et al. 2013).

Climate warming has been considered as the reason for accelerated wheat growth rates and shortened winter wheat-growing periods (Tao et al. 2006; Chen et al. 2010c; Liu et al. 2010; Xiao et al. 2012a). In response to climate warming, the NCP winter wheat producers have found it necessary to adjust the agrarian calendar because anthesis and maturity are occurring earlier than in the past (Xiao et al. 2012a), and some researchers reported that the time between planting and anthesis continues to shorten (Tao et al. 2012). However, there are solid indications based on data from the last three decades that the length of the post-anthesis period has stabilized (Tao et al. 2006, 2012; Liu et al. 2010; Xiao et al. 2012a). Although climate warming-induced phenology changes have been observed, the mechanism by which climate change interacts with cultivar development in affecting crop growth and yield is not yet well understood.

The combination of climate warming and reduction in solar radiation may explain the declining winter wheat yield (Tao et al. 2008; You et al. 2009; Piao et al. 2010). You et al. (2009) found that winter wheat yields are reduced by 3–10 % for every 1 °C increase in the winter wheat-growing season temperature. Using a crop model, Chen et al. (2013) suggested that the decreasing trend in solar radiation may have a much greater negative impact than warming climate upon winter wheat yields. Compared to the no-climate-change condition, a global net loss of 5.5 % was found in practical wheat production from 1980 to 2008 (Lobell et al. 2011). Despite these negative climatic factors, there has been tremendous progress in wheat production, and the national average yield in China increased from 0.64 in 1950 to 3.90 Mg ha⁻¹ in 2005 (Zhou et al. 2007a). Although this progress is due largely to the changes in crop management practices, such as selecting the best sowing date, more irrigation, and chemical fertilizer use, the development of new cultivars has contributed as well (Tian et al. 2012).

An understanding of how alternative cultivars would impact the potential crop yield and alter phenology is essential to improving wheat production. Although previous studies on wheat cultivars have found a significant increase in both the harvest index (HI) and kernel number, there were no common trends in biomass, thousand kernel weight, or kernels per spike (Zhou et al. 2007a, b; Foulkes et al. 2011; Parry et al. 2011; Reynolds et al. 2011; Tian et al. 2011; Xiao et al. 2012b). Reynolds et al. (2011) noted that the fundamental bottleneck to increasing productivity is how plants use solar radiation; indeed, after years of wheat breeding research, the radiation use efficiency (RUE) value has barely changed.

Instead, new cultivars require more thermal time for development, thus prolonging the growth period (McMaster et al. 2008; Tao et al. 2012).

Two approaches have generally been used for understanding the influences of cultivar upon grain yield and phenology. One approach involves analyzing crop yield and phenology data from regional trials collected over relatively long periods of time using some common check cultivar. The other approach refers to comparing old and modern cultivars that have been grown together in specifically designed experiment (Zhou et al. 2007a). However, these approaches are not able to quantify the relative influence of climate and cultivar on the potential yield and phenology. Process-based crop models provide a means of quantifying individual or combined influences on crop yield and phenology (Ren et al. 2012). Such crop models can provide estimates of crop growth under perfect conditions (no water and nutrient limitation, diseases, and pests controlled) (Lobell et al. 2009), and only impacts of changing cultivar physiology and climate on crop growth are considered.

Objectives of this study were as follows: (1) to analyze changes in phenology, thermal time, and production characteristics triggered by winter wheat varieties undergoing climatic change; (2) to determine the influence of climate change on winter wheat phenology and winter wheat grain yield; and (3) to quantify the compensating effect of cultivar development on the phenology and yield potential of winter wheat in multiple agricultural regions in the NCP.

Materials and methods

To study the climate change and cultivar development effects on wheat yield, an approach combining empirical analysis and simulation modeling was applied in this study. Firstly, crop parameters were selected based on crop model traits to reflect actual cultivar development. The second, based on measured data, we quantified the main characteristics of the cultivar development according to the crop model parameters. In the last section, simulation scenarios were set up to address the individual effects of climate and cultivar selections on wheat growth.

Study area

The NCP study area includes Hebei, Henan, and Shandong Provinces and the cities of Beijing and Tianjin (Fig. 1). The typical cropping system in the region is a rotational scheme, according to which winter wheat and summer maize are planted in the same area. Suitable climatic conditions and good soil quality favor extensive winter wheat production (Tao et al. 2006). Six sites were selected to reduce bias in our analysis considering that winter wheat could potentially be influenced by a variety of environmental factors. Factors

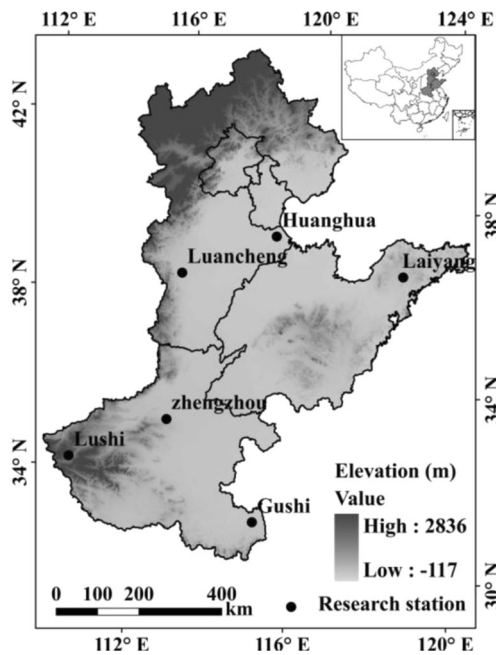


Fig. 1 Research area and sites. Gushi, Lushi, and Zhengzhou located in Henan province; Laiyang located in Shandong province; Huanghua and Luancheng located in Hebei province

considered in site selection included agro-ecological production zones (Li et al. 2010), elevations, and geographic locations (Table 1). Table 1 and Fig. 1 provide information about site location, soil property, and plant phenology, etc. Based on all available data, we focused only on the period from 1981 to 2005, which the NCP has been experienced a rapid development of breeding techniques (Ding et al. 2006; Xu et al. 2013). All of the sites have loam-like soil, the main soil type in the NCP. The annual maximum and minimum air temperatures and precipitation decrease from south to north; in contrast, the annual total solar radiation increases from south to north. Each site had a standard weather station for collecting daily weather observations and an agricultural meteorological station that collected data on crop variety, plant growth, and crop yield.

Climate and crop data

Daily records of maximum and minimum temperatures, sunshine hours, and precipitation were available from 1981 to 2005 at each weather station. To determine the amount of daily solar radiation, we used the Angstrom formula (Black et al. 1954; Jones 1992) to generate decent estimates. This formula has been widely used in the NCP and expressed high effectiveness (Wu et al. 2008; Liu et al. 2010, 2013).

With regard to the agricultural data, we viewed data on the wheat phenology (sowing, emergence, anthesis, and maturity dates), cultivar types, aboveground dry materials, crop yields, and agrarian practices. Crop management practices at the experiment stations included more fertilizer, weed control, and higher sowing density than the prevalent local practices (Tao

et al. 2006) and did not have significant change during the research period; thus, the yield change mainly owed to climate and cultivar change. The experiment stations were maintained by the China Meteorological Administration (CMA), and the observational criteria were in accordance with CMA observation standards (China Meteorological Administration 1993). Here, wheat phenology was observed when 50 % of plants reached the specific stage; wheat biomass and yield were observed when weight difference at intervals of 1 h was less than 5‰ during the process of drying. The crop productivity characteristics included details such as the number of spikes per square meter, number of kernels per spike, thousand kernel weight, kernel weight per spike, and harvest index (HI). Wheat cultivars were frequently changed during the study period, and we found that several new crop cultivars were released by crop seed and breeding stations during the period from 1981 to 2005. The selection of wheat cultivars used at each station followed the cultivar change as influenced by cultivar released and adopted by local farmers. Therefore, the cultivars at the time were representative of the widely used crop cultivars from the north to south parts of the NCP (Liu et al. 2010).

In this study, we defined the wheat growth period (GP) to be the period from sowing to maturity, and we defined the vegetative growing period (VGP) to be the period from sowing to anthesis. We needed these two definitions because we wanted to differentiate when the vegetative organs are produced. We defined the reproductive growing period (RGP) as the period from anthesis to maturity, which is the main stage for grain growth (Liu et al. 2010).

APSIM model and data analysis

The Agricultural Production Systems Simulator (APSIM) was used to simulate the wheat phenology and potential crop yields in response to changes in environmental factors and cultivars during the 1981–2005 period. We selected the APSIM model because it has been well tested and widely used in Australia (McCown et al. 1996; Asseng et al. 1998; Keating et al. 2003) and recently been validated in the NCP (Wang et al. 2007; Chen et al. 2010a, b; Zhang et al. 2012). These studies indicated that APSIM-simulated results showed a high degree of congruence with the observed crop growth, actual yield, and actual water consumption. The model can explain more than 80 % of the variation in crop biomass and yield. We relied on the APSIM model validation to assess the performance of our model. The APSIM model uses 11 crop stages and 10 “interstages” (time between stages) or phases. The crop stage names are sowing, germination, emergence, end of the juvenile stage, floral initiation/terminal spikelet, anthesis, start of grain filling, end of grain filling, physiological maturity (maturity), harvest ripe, and end of crop life (for more details, see www.apsim.info). The commencement of each phase is determined by the sum thermal time cumulated

Table 1 Soil type, varieties, and phenology characters in the year of 1981 and annual average maximum, minimum temperature, and annual total precipitation and radiation in 1981–2005

Locations	Soil type	Varieties	Phenology (day-month)				Climatic factors			
			Sowing	Emergence	Anthesis	Maturity	T_{\max} (°C)	T_{\min} (°C)	Rad (MJ m ⁻²)	P (mm)
Gushi	Clay loam	Boai7023	3-Nov	15-Nov	28-Apr	30-May	20.3	12.1	5381	1093
Zhengzhou	Sandy loam	Zhengzhou761	7-Oct	13-Oct	27-Apr	28-May	20.2	9.7	5316	637
Lushi	Loam	Zhengyin1	26-Oct	6-Nov	10-May	15-Jun	19.4	7.5	5315	643
Luancheng	Clay loam	Pin39	1-Oct	7-Oct	6-May	8-Jun	19.5	9.1	5369	512
Huanghua	Sandy loam	Taishan1	4-Oct	11-Oct	10-May	6-Jun	18.6	8.2	5574	526
Laiyang	Loam	Jinan13	6-Oct	16-Oct	16-May	19-Jun	18.1	6.9	5786	647

from daily thermal time values, with the exception of the time from the sowing stage to the germination stage, which is driven by the soil water content. According to the method in APSIM (www.apsim.info), we calculated the thermal time using three-hourly temperatures interpolated from the daily maximum and minimum temperatures, and then, the eight thermal times were averaged into the daily thermal time. The maximum and minimum crown temperatures were simulated with maximum and minimum air temperature according to the original routines in CERES-Wheat (Sadras and Monzon 2006).

According to the APSIM-Wheat model, the thermal time needed for the period from germination to emergence stage was determined by the sowing depth and an initial fixed thermal time. Therefore, this thermal time is unchanged in this study period, since the sowing depth is fixed. The end of the juvenile phase is currently timed as occurring on the day after emergence. The thermal time needed from the end of the juvenile to the floral initiation stage is constant (400 °C day), but the rate of development is influenced by vernalization and photoperiod which are cultivar decided. There is fixed thermal time for the period from the floral initiation to anthesis stage, and the thermal time from anthesis to the start of grain filling stage is assumed to be 120 °C day. The duration of grain filling (from the start of grain filling to physiology maturity) is cultivar specific. To address the effects of cultivar on phenology and yield, we focused the change of vernalization, photoperiod, and the thermal time duration of grain filling in this study.

In the APSIM model, the grain yield is restricted by the most limiting factor, which could be the size of the sink (kernels per unit area, potential rate of kernel filling, and maximum kernel size) or the size of the source (photosynthesis, quantity of stored assimilates available for remobilization, and duration of kernel filling) (Asseng et al. 2002). Since the insignificant change of photosynthesis and the difficulty to qualify the change of stored assimilates available for remobilization, we assumed these factors were unchanged in the whole period.

The cultivar control parameters (CCPs) that we focused in the APSIM model are divided into two groups: crop development control parameters (CDCPs) and crop productivity

control parameters (CPCPs). The CDCP group includes vern_sens (A_v , sensitivity to vernalization), photop_sens (A_p , sensitivity to photoperiod), and tt_startgf_to_mat (P , thermal time from beginning of grain filling to physiological maturity, °C day). The vern_sens parameter and photop_sens parameter together determine the development rate (time) from the end of the juvenile phase to the floral initiation phase. These two parameters are associated with the anthesis date. To accommodate pre-anthesis phenology change, we adjusted them by trials accordingly (Liu et al. 2010), such that the simulated anthesis dates could match the measured anthesis dates for each year and these two parameters could represent the change of pre-anthesis stage during simulation. Details for each parameter are listed in Table 2. The period from anthesis to maturity (the RGP period) could be divided into one stage from anthesis to start of grain filling and another stage from start of grain filling to maturity. The length of time from the start of grain filling to maturity was determined by the tt_startgf_to_mat parameter which was the value of thermal time in this stage. The thermal time in RGP (the stage from anthesis to maturity) could be computed by measured anthesis and maturity dates and air temperature. And then, the tt_startgf_to_mat parameter could be calculated by the thermal time in RGP minus 120 °C day which was the thermal time from anthesis to the start of grain filling assumed by APSIM model. More details are provided in Table 2.

The CPCP group includes grain_per_grain_stem (K , coefficient of kernel number per stem weight at the beginning of grain filling, kernel g stem⁻¹), potential_grain_filling_rate (R , potential grain-filling rate, g grain⁻¹ day⁻¹), and max_grain_size (M , the maximum weight per grain, g). To quantify how the cultivar and sowing date influence the potential winter wheat yield, eight scenarios were developed and are listed in Table 2.

The wheat cultivars used in 1981 for each site are listed in Table 1. Based on the former validation of APSIM-Wheat model (Wang et al. 2007; Chen et al. 2010a, b; Zhang et al. 2012), the CCPs listed in the Tables 3 and 4 were adjusted using measured wheat yield and phenology data of each site in

Table 2 Treatments used in model experiment

Treatments	Characteristics	Model parameters	Changes	Comments
CDCP	A Changing vegetable period	Sensitivity to vernalization Sensitivity to photoperiod	Fit measure anthesis date each year	Cultivar-specific parameter; these two parameters control the development rate from emergence to terminal spikelet which takes constant degree day. Value becoming bigger means need more thermal time.
P	Increasing kernel filling period	Thermal time from beginning of grain filling to maturity	Eqs. 1 and 2	Cultivar-specific parameter; calculate the thermal time from beginning of kernel filling to maturity through measuring phenology and use its slope against time for parameter changing per year.
CPCP	K Kernel number per biomass	Coefficient of kernel number per stem weight at the beginning of grain filling (g stem ⁻¹)	Eqs. 1 and 2	Cultivar-specific parameter; using the slope calculated from measuring data for per year changing rate
R	Increasing kernel filling rate	Potential grain-filling rate (g grain ⁻¹ day ⁻¹)	Eqs. 1 and 2	Cultivar-specific parameter; same as above
M	Increasing max kernel size	Max weight per grain (g)	Eqs. 1 and 2	Cultivar-specific parameter; same as above
C _v	Combination of CDCP and CPCP	–	Same as CDCP and CPCP	Cultivar change influences the potential yield
S	Sowing date	–	Measured date	Management changing toward to climatic change
C	Combination of CDCP, CPCP, and S	–	Same as all above	Total influence to potential yield

1981. We assumed that the CCPs in 1981 were the initial cultivar-specific parameters at each site. To catch the cultivar change in past, we adjusted the CCPs following the experimental data. We assumed that the trend (*k*) of measured data could represent the trend of CCPs. For instance, the *tt_startgf_to_mat* parameter could be used in the same fashion as the thermal time variable in RGP because the thermal time from anthesis to the start of grain fill was assumed to be 120 °C day in the APSIM-Wheat model. The *k* of the *max_grain_size* parameter would have the same value as the *k* of the thousand kernel weight parameter because the *max_grain_size* was given a working value of thousand kernel weight. The *grain_per_gram_stem* was from the kernel number and stem weight. For the *potential_grain_filling_rate* parameter, we used the grain weight and the length of RGP (www.apsim.info).

A linear regression analysis with respect to time was used to calculate the trend (*k*) of the experimental data. The statistical significance was determined using two-tailed *t* tests after normality test using Kolmogorov-Smirnov (K-S) model in SPSS. The equations were given below:

$$Y_i = k \times i + b \quad (i = 1981, 1982, \dots, 2005) \quad (1)$$

$$CCP_{i+1} = CCP_i + k \quad (i = 1981, 1982, \dots, 2004) \quad (2)$$

where *Y_i* is the wheat variety characteristics computed using the data measured at the agricultural-meteorological experiment stations in year *i*. The other variables are defined with *i* as the year, *k* as the trend, and *b* as the intercept. The CCP_{*i*} term in Eq. 2 is based on the CCP value used in the APSIM-Wheat model for each year *i*: the CCP_{*i*+1} term represents the CCP in the year *i*+1. The 1981 base year term, CCP₁₉₈₁, is listed in Tables 3 and 4.

To address the potential impact of cultivar and climate to the wheat yield, we used crop model to calculate the potential yield in this study. Potential yield is the highest yield that could be achieved in a given location under a certain crop cultivar without any biophysical limitations (such as water, nutrient, disease, and pest) other than uncontrollable factors, such as solar radiation and air temperature (Evans and Fischer 1999; Grassini et al. 2009; Lobell et al. 2009). It is a key index of scientifically appraising crop production and land population-supporting capacity (Evans and Fischer 1999).

Results

Wheat phenological characteristics and CCP trends

Winter wheat is generally sown from September to November in the NCP (Fig. 2). The graphs labeled a₁ through f₁ in Fig. 2 show the sowing dates for winter wheat from 1981 to 2005.

Table 3 Average measured values of wheat growth period (GP), vegetable growth period (VGP), reproduction growth period (RGP), and calculated thermal time in each period in 1981–2005 and these trends against time

Items			Gushi	Lushi	Zhengzhou	Huanghua	Luancheng	Laiyang
Growing period	Average (day)	GP	210	240	227	248	248	256
		VGP	177	205	192	222	215	223
		RGP	33	35	35	26	33	33
	k (day year ⁻¹)	GP	-0.020	-0.210	-0.022	-0.395	-0.052	-0.580**
		VGP	-0.213	-0.187	-0.203	-0.383	-0.320*	-0.481*
		RGP	0.193	-0.023	0.181	-0.012	0.268**	-0.099
TT	Average (°C day)	GP	2201.8	2188.5	2171.9	2135.2	2348.9	2165.3
		VGP	1499.0	1460.4	1430.7	1558.8	1617.5	1465.5
		RGP	702.8	728.1	741.2	576.3	731.4	699.8
	k (°C day year ⁻¹)	GP	10.918*	6.193	12.045**	4.386	10.484**	3.057
		VGP	8.024	6.792	8.320*	4.210	5.339	4.277
		RGP	2.894	-0.599	3.725*	0.176	5.144**	-1.220
CDCP	1981 ⁺	tt_startgf_to_mat	580	630	520	450	570	620
		vern_sens	1.8	2.2	2	2.5	2.6	2
		photop_sens	2.5	3.1	2.5	3.2	2.8	2.5
	k	tt_startgf_to_mat	2.894	-0.599	3.725*	0.176	5.144**	-1.220
		vern_sens	0.0301**	0.024	0.020	0.008	0.011	0.008
		photop_sens	0.0416**	0.026	0.030	0.008	0.009	0.015

The values of CDCP, in the year of 1981, are given, and these trends against time are calculated by measured data. k is the trend of linear regression against year. “+” means Laiyang’s CDCP is 1982

**Significant at $P < 0.01$; *Significant at $P < 0.05$

Over this time period, sowing was delayed in the northern areas (Huanghua, Luancheng, and Laiyang) but was advanced in the southern areas (Gushi, Lushi, and Zhengzhou), with the most significant change recorded in Gushi (7.6 days per

decade). The pattern was different for anthesis, which occurred earlier (more than 2 days per decade) over time for all sites, with significant changes in Gushi, Lushi, Zhengzhou, Luancheng, and Laiyang (Fig. 2, graphs a_2 through f_2). The

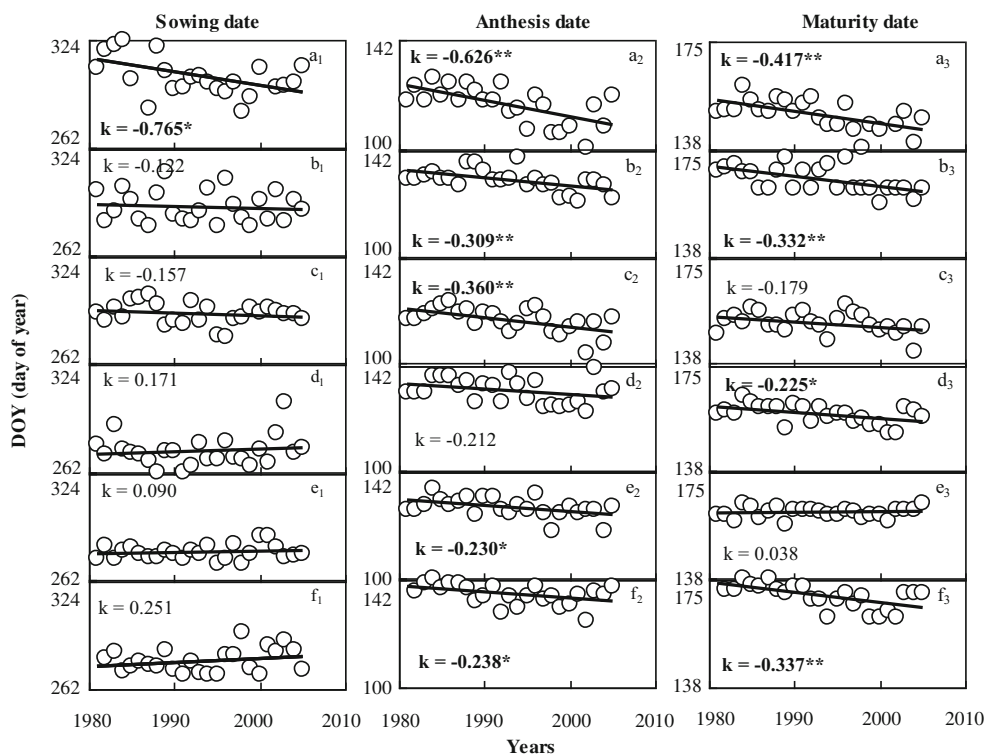
Table 4 Average values of thousand kernel weight, spike per square meter, and harvest index in the year of 1981–2005 and its trend against time

Items			Gushi	Lushi	Zhengzhou	Huanghua	Luancheng	Laiyang	
Grain productive characters	Thousand kernel weight (g)	Average	35.5	37.5	40.9	29.3	36.1	33.5	
		k	-0.054	0.309**	-0.063	0.226	0.048	0.055	
	Spike per square meter	Average	430	653	532	394	667	552	
		k	1.006	8.213	10.150**	-12.217**	3.181	-11.704*	
	Kernels per spike	Average	27.7	41.0	32.4	22.5	28.2	34.7	
		k	0.077	-0.073	0.292*	-0.184	0.301**	0.322	
	Harvest index (%)	Average	38.7	39.3	37.9	36.4	43.5	46.5	
		k	0.678**	0.367	1.013**	0.615**	0.491**	0.812**	
	CPCP	potential_grain_filling_rate (mg grain ⁻¹ day ⁻¹)	1981 ⁺	2.8	1.9	2.1	2.0	2.1	2.1
			k	-0.004	0.036*	-0.009	0.010*	-0.007	0.005
grain_per_gram_stem (kernel g stem ⁻¹)		1981 ⁺	27.0	26.0	23.0	24.0	25.0	27.0	
		k	0.595**	0.124	0.700**	0.468**	0.470*	0.748**	
max_grain_size (g)		1981 ⁺	40	39	45	40	40	38	
		k	-0.054	0.309**	-0.063	0.226	0.048	0.055	

The values of CPCP, in the year of 1981, are given, and these trends against time are calculated by measured data. k is the trend of linear regression against year. “+” means Laiyang CDCP is 1982

**Significant at $P < 0.01$; *significant at $P < 0.05$

Fig. 2 Trends of sowing day (a_1-f_1), anthesis day (a_2-f_2), and maturity date (a_3-f_3) in Gushi (a_1-a_3), Lushi (b_1-b_3), Zhengzhou (c_1-c_3), Huanghua (d_1-d_3), Luancheng (e_1-e_3), and Laiyang (f_1-f_3). Straight line is the linear regression line against year. **Significant at $P < 0.01$; *significant at $P < 0.05$



maturity date changes were similar, with the Luancheng site being the only exception (only -0.4 days per decade) and with significant changes in Gushi, Lushi, Huanghua, and Laiyang (Fig. 2, graphs a_3 through f_3).

It is typical that the northern areas have longer GP values—approximately 230 days. However, from 1981 to 2005, the GP length decreased, with Laiyang exhibiting the greatest reduction (5.8 days per decade). The changes in the VGP values were similar to the GP changes, and the baseline value was 200 days; the changes were significant for Luancheng (3.2 days per decade) and for Laiyang (4.8 days per decade). However, the RGP values exhibited a diverse trend. In 1981, the length of RGP was around 30 days, and it slightly shortened at three sites but lengthened at other three sites over the studied period, with significant increases for Luancheng (Table 3).

The thermal time during GP, unlike the length of GP, exhibited no obvious variations northward and was approximately 2200 °C day during the study period. Both the GP thermal time and VGP thermal time increased every year during the period of 1981–2005, with particularly significant GP increases for Gushi, Zhengzhou, and Luancheng and particularly significant VGP increases for Zhengzhou. Although the thermal time during RGP did not exhibit the same trends across all the six sites, decreasing slightly for Lushi and Laiyang, it indicated a significant increase at Zhengzhou and Luancheng.

As the $tt_startgf_to_mat$ parameter was only controlled by thermal time, it had the same trend as the RGP thermal time.

Additionally, all the sites experienced increases for both the $vern_sens$ and $photo_sens$ parameters, with significant increases for Gushi, due to the heightened wheat growth phase thermal time.

Wheat productivity characteristics and cultivar production control parameter trends

Except for a significant increase in HI appeared for five of six sites, the values of the thousand kernel weight, spike per square meter, and kernels per spike did not display the same trends across sites (see Table 4). The values of the thousand kernel weight increased for Lushi, Huanghua, Luancheng, and Laiyang, with a significant increase for Lushi, but decreased slightly for Gushi and Zhengzhou. The values of the spike per square meter did not increase in the same pattern as those of the thousand kernel weight: there were increases for Gushi, Lushi, Zhengzhou, and Luancheng, with a significant increase for Zhengzhou, but significant decreases for Huanghua and Laiyang. The values of kernels per spike increased for Gushi, Zhengzhou, Luancheng, and Laiyang, with a significant increase for Zhengzhou and Luancheng, but decreased slightly for Lushi and Huanghua.

Table 4 also shows that $potential_grain_filling_rate$ increased for Lushi, Huanghua, and Laiyang, with a significant increase for Lushi and Huanghua, but decreased for Gushi, Zhengzhou, and Luancheng. The values for the $grain_per_gram_stem$ parameter are in line with the HI values, which increased for all sites. The max_grain_size parameter

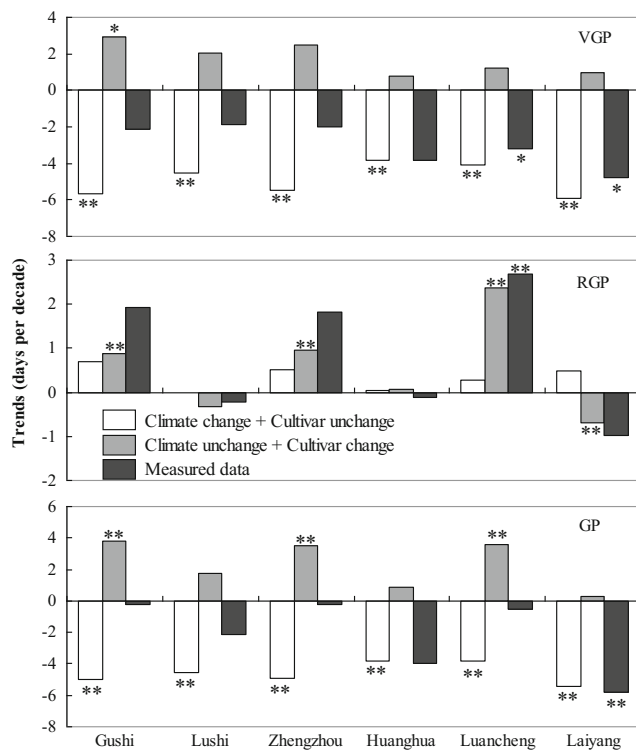


Fig. 3 Trends of simulated vegetable growth period (VGP), reproductive growth period (RGP), and growth period (GP) against time. Two scenario simulations were used to find out the effect of climate and cultivar to growth period. The first scenario is controlling cultivar but changing climate through 1981 to 2005 (white bar), and the second is contrary, controlling climate and changing cultivar (gray bar), and the measured trend of growth period is also listed (dark gray bar). **Significant at $P < 0.01$; *significant at $P < 0.05$

also appears to be in synchronization with the thousand kernel weight values.

Cultivar traits and climate change influence on wheat phenology and potential yield

Wheat phenology

Using the APSIM model, it is possible to separate the effects of climate change and cultivar development on the winter wheat phenology over the past three decades. In Fig. 3, the white bars show how GP and VGP were significantly shortened (3.8–5.4 days per decade and 3.8–5.9 days per decade, respectively) for all six sites, whereas the RGP values were slightly extended (−0.02–0.7 days per decade) as a result of the influences of climate change and cultivar control.

The APSIM model was used to simulate a climate-controlled environment to explore the effect of cultivar changes on phenology. In Fig. 3, the gray bars show how the GP values increased for all six sites (0.3–3.8 days per decade), with significant increases for Gushi, Zhengzhou, and Luancheng. The VGP values experienced similar increasing trends (0.8–2.9 days per decade), with the only significant

increase occurred at Gushi. In contrast, the effects on the RGP values were divergent: the RGP values increased for Gushi, Zhengzhou, Huanghua, and Luancheng (by 0.9, 1.0, 0.07, and 2.4 days per decade, respectively), with significant increases for Gushi, Zhengzhou, and Luancheng, but decreased for Lushi and Laiyang (by −0.3 and −0.7 days per decade, respectively), with a significant decrease for Laiyang.

Potential wheat yield

The APSIM model showed that climate change had a negative influence on potential wheat yield. Figure 4 shows that, when cultivar change was controlled, the potential winter wheat yield decreased for five sites as a direct result of climate change (−3.3 to −54.8 kg ha^{−1} year^{−1}), with a significant decrease for Zhengzhou. The only exception was Lushi, which experienced an increase of 39.1 kg ha^{−1} year^{−1}. If the APSIM model is adjusted to include the influence of cultivar development, the potential winter wheat yield was improved by 5.0 to 19.4 %, with significant increases for Gushi and Lushi (41.7 and 139.7 kg ha^{−1} year^{−1}, respectively) and a decrease for Luancheng (3.3 kg ha^{−1} year^{−1}).

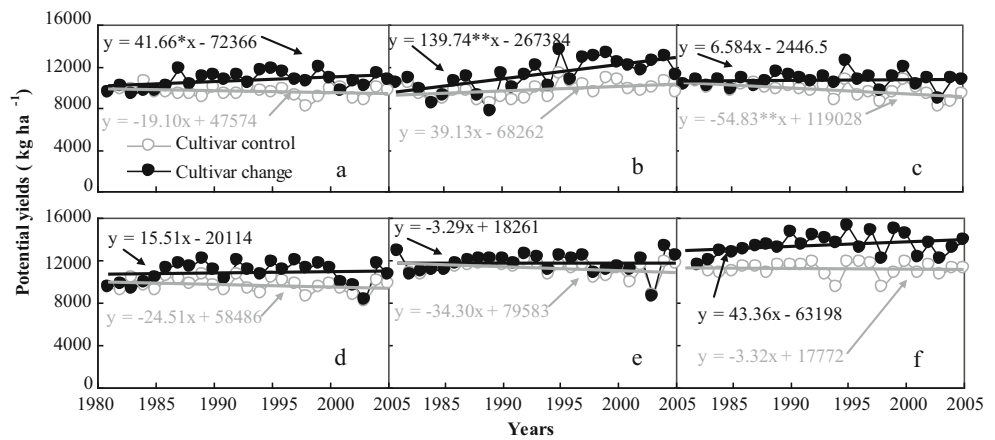
Discussion

Phenology

In this paper, the timing of anthesis and the timing of maturity in the NCP occurred earlier and led to a decrease in the lengths of GP and VGP but an increase or no significant trend in the length of RGP (Fig. 3). Previous studies have indicated that temperature was the major governing factor during crop GP (Kirby et al. 1987; Tao et al. 2006, 2012; Liu et al. 2010; Xiao et al. 2012a). It is clear that the lengths of GP, VGP, as well as RGP were temperature driven. High temperatures accelerate crop growth rates and shorten the length of GP (Fig. 5a). Further analyses have shown that an earlier anthesis date caused by climate warming may result in the advance of the grain-filling period, because the temperature in RGP should be lower in the condition of earlier anthesis, compared with the condition of anthesis unchanged (Ludwig and Asseng 2010; Tao et al. 2012).

The phenology of winter wheat is also influenced by genetic variables (Kirby et al. 1987). The new cultivars require more thermal time to complete development, which could compensate for the negative effect of climate warming while prolonging the GP, which is consistent with the findings of previous studies (McMaster et al. 2008; Liu et al. 2010; Tao et al. 2012). Liu et al. (2010) noted that the simulated reduction in the length of the GP of wheat was greater than that found by Tao et al. (2006) in actual production when the

Fig. 4 Effect of cultivar change on potential yield of winter wheat under climate change in 1981–2005 in the NCP. Gushi (a), Lushi (b), Zhengzhou (c), Huanghua (d), Luancheng (e), and Laiyang (f) are simulated. The scenarios of cultivar control (open point) and cultivar change (filled point) are listed. Straight line is the linear regression line against year. **Significant at $P < 0.01$; *significant at $P < 0.05$



counteractive effects of cultivar changes were eliminated from the simulation.

Results of this study showed that climate warming has contributed substantially to the shift in wheat phenology in the NCP during the study period. The climate of the NCP has been projected to be warmer in the future (Ding et al. 2006; Fu et al. 2009), which will have a further negative impact on wheat phenology (Lin et al. 2007). Thus, wheat cultivars with longer GPs should be adopted to offset the negative impact to secure crop production in the NCP (Liu et al. 2010).

Potential yield

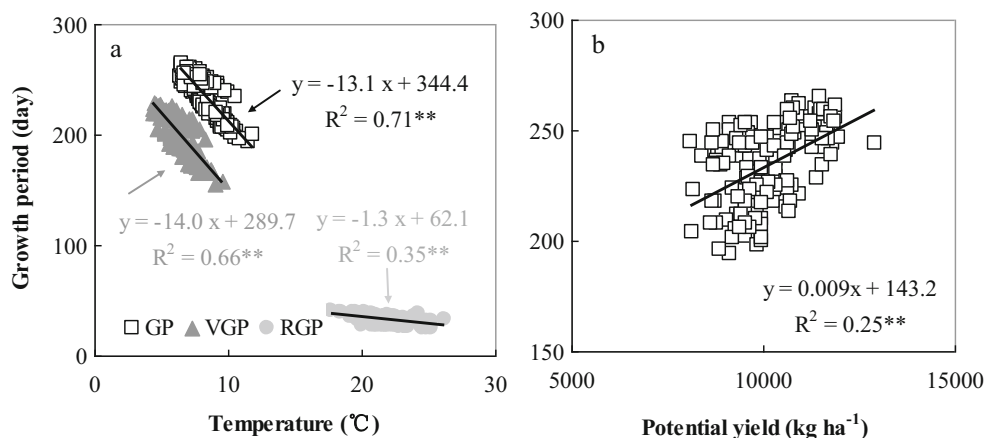
The results of our study indicated that the potential yield of winter wheat will decrease at all sites other than Lushi as a result of climate change if cultivar development was not considered (Fig. 6). Previous studies have also found that climate change had a negative effect on potential wheat yield (Bell and Fischer 1994; Pathak et al. 2003; Luo et al. 2005; Chen et al. 2010c, 2013; Li et al. 2010; Liu et al. 2010). Precipitation has been identified as an important driver of the interannual variability in winter wheat yield. However, Lobell et al. (2011) estimated a global net loss of 5.5 % in wheat yield from 1980

to 2008 compared to the no-climate-change condition, and the majority of the impact is driven by trends in temperature rather than trends in precipitation. Chen et al. (2013) found that decreasing solar radiation had a much greater negative impact than increasing temperature on potential wheat yield in the NCP from 1961 to 2003. In this study, we found that decreases in the potential yield were attributable to decreased solar radiation during the GP which resulted from increased average temperature and sunlight dimming (Fig. 6).

The increase in the potential wheat yield due to cultivar development has been measured in many studies. Most studies have reported no change in biomass (Austin et al. 1980; Waddington et al. 1986; Cox et al. 1988; Sayre et al. 1997; Brancourt-Hulmel et al. 2003; Zhou et al. 2007a; Parry et al. 2011), whereas a few studies have found that increased biomass is associated with improved cultivars (Perry and D’Antuono 1989; Siddique et al. 1989; Shearman et al. 2005; Xiao et al. 2012b). The higher harvest index (HI) and kernel number per square meter were identified as the major cultivar characters to increase wheat grain yield (Brancourt-Hulmel et al. 2003; Shearman et al. 2005; Peltonen-Sainio et al. 2007; Zhou et al. 2007a; Xiao et al. 2012b).

Phenology changes (CDCPs) caused by cultivar improvement were found to have positive effects on the potential

Fig. 5 a The relationship between average temperature in growth period (GP), vegetable growth period (VGP), and reproductive growth period (RGP) and the length of the growth periods and b the relationship between potential yield of winter wheat and growth period (GP). Straight line is the linear regression line against year. **Significant at $P < 0.01$; *significant at $P < 0.05$



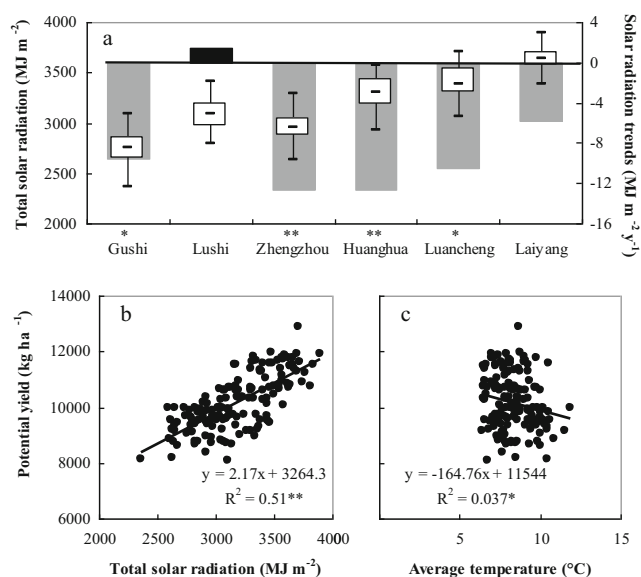


Fig. 6 Total solar radiation (box) in simulated winter wheat GP and its linear trends (bar) against year in six sites (a) and the relationship between total solar radiation (b) during GP and potential yield, between average temperature (c) during GP and potential yield. The clear horizontal line within each box gives the average total solar radiation, the upper and lower edges of each box give the 25 and 75 % percentiles, and the error bars indicate minimum and maximum solar radiation during 1981 to 2005. Black bar means increase trends. In contrast, gray bar means decrease trends. Asterisk means the significance of trends in Fig. 6a. **Significant at $P < 0.01$; *significant at $P < 0.05$

wheat yield. Within the significant trend of anthesis date advancement, delayed anthesis resulting from cultivar development increased the potential yield; in contrast, early anthesis had a negative influence. Considering the influences of climate warming and cultivar development on phenology together, anthesis date of winter wheat occurred early (Xiao et al. 2012a). In contrast, cultivar development could delay the anthesis dates compared with cultivar-controlled condition which showed that the delays were 2.6, 3.0, 3.7, 0.6, 2.2, and 1.1 days in Gushi, Lushi, Zhengzhou, Huanghua, Luancheng, Laiyang, respectively.

It is unlikely that further large increases in HI will occur, but an opportunity exists for increasing productive biomass and harvestable grain (Foulkes et al. 2011; Parry et al. 2011; Reynolds et al. 2011), and the potential wheat yield could theoretically be increased by up to 50 % through the genetic improvement of the radiation use efficiency (RUE) (Foulkes et al. 2011; Parry et al. 2011; Reynolds et al. 2011). In addition, increases in the kernel number per square meter remain strongly associated with further genetic progress in grain yield (Fischer 2007).

Uncertainty analysis

Rising in atmospheric CO_2 concentration from about 339 ppm in 1981 to about 379 ppm in 2005 is well documented (IPCC

2007). Although it is clear that higher CO_2 has a fertilization effect and could increase water use efficiency in wheat production, there is still a subject of considerable debate about the positive impacts of CO_2 elevation on wheat production. In this study, CO_2 level was set constant at 340 ppm during research period. This setting would lead to omit the positive effects of rising CO_2 and overestimate the negative effects of climate change to wheat production. The overestimation could research 3 % of wheat production, according to the study of Lobell and Gourdji (2012).

In this study, we used a crop model to depict the traits of phenology and yield component during cultivar change. However, approximately 347 cultivars were released and introduced into the national seed market in China from 1984 to 2010. The large number of cultivar options in China makes accurate identification of cultivar improvement traits difficult. On the other hand, even in one site, it is difficult to use crop model to catch all of the traits of cultivar change because of the limiting of measured data and model frame, especially the traits of some physiological features (e.g., plant resistance).

Current crop model, for example APSIM and CERES, assumed that thermal time accumulation of crops during the growing season remains constant under various climate conditions. However, some researchers indicated that the thermal time accumulation for the entering growing season was not constant (Zhang et al. 2008). Crop model with constant thermal time accumulation will significantly underestimate the observed phenological trend over long time period (Zhang et al. 2008). This assumption should have added some uncertainty to the model simulations in this study.

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