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Full Length Article

Assessing the Impacts of Climate Variables and Sowing Date on Spring Wheat Yield in the Northern China

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Abstract

As climate change could significantly exert impacts on crop growth and productivity, sowing date adjustment is a critical measure to mitigate and adapt to the climate change. Thus, in this study, field-observed experiments at six stations in the Northern China (NC) are used in combination with the APSIM–Wheat model to assess the impact of climate variables and sowing date on spring wheat yield during the study period of 1981–2010. The results indicated that climate change during the past 30 years in NC exerted negative impacts on yield of spring wheat at the all investigated stations except Haixi. The temperature has gone beyond the optimum temperature of the spring wheat growth at the most selected stations in this study region. The decrease in solar radiation did not exert negative impact on the yield of spring wheat in NC. The findings further suggested that radiation is not the main limit factor for spring wheat growth and productivity at the most parts in NC region. The impacts of precipitation on spring wheat yield are slight and insignificant. Furthermore, the impacts of changes in sowing date (SD) on spring wheat yield are different in the different systems (rain-fed and irrigated). Under rain-fed conditions, delay in SD will slightly enhanced spring wheat yield due to the improvement in the availability of water with the delay in start of wheat growing season. However, under irrigated conditions, early sowing will be resulted in increased yield of spring wheat.

Keywords: Adaptation; Grain yield; Climate change; Sowing date; Northern China

Introduction

There is now a general consensus in the scientific community regarding warming climatic conditions in recent decades (IPCC, 2013). Food security could be under threat due to the effects of climate change on regional, national and even global grain production (Lobell and Field, 2007; Asseng *et al*., 2015; Liu *et al*., 2016b). Hence, the impacts of climate change on crop production in the China and world has increased (Lobell *et al*., 2011; Butler and Huybers, 2013; Xiao and Tao, 2014, 2016; Liu *et al*., 2016a). While recent study indicate that global wheat yield is projected to drop between 4.1% and 6.4% under global temperature increase 1°C (Liu *et al*., 2016a), winter wheat yield under irrigated conditions in the North China Plain is increased by 3.0%–6.0% due to temperature increased (Xiao and Tao, 2016). Thus, due to the different climatic conditions in different study areas, the responses of crop grain yield to climate change are also different (Tao *et al*., 2014; Ewert *et al*., 2015; Xiao and Tao, 2016). In order to more objectively reflect the impacts of climate change on crop growth and productivity, we need to carry out related researches for different regions and different crops (including planting the same crop in different modes, such as spring wheat and winter wheat) (Semenov, 2015).

In the Northern China (NC), due to lower temperature in winter reason, it can only grow one season crop during one year (Yang *et al*., 2011). Spring wheat is a staple crop cultivated in NC (Xiao *et al*., 2016). Generally, spring wheat is sown in early March to late April, and maturity is generally in late June to early September in this region (Xiao *et al*., 2016). Previous study has investigated the trends in the dates of spring wheat phenology in relation to mean temperature for different growth stages (Xiao *et al*., 2016; Zhu et al., 2015). The results showed that significant changes have occurred in spring wheat phenology in NC due to climate warming (Xiao *et al*., 2016). Furthermore, shift in sowing date (SD) exert significantly impacts on the phenology of spring wheat (White *et al*., 2011). To a large extent, crop yield is influenced by the timing/length of various phenological stages/phases (Cirilo and Andrade, 1994; Jamieson *et al*., 1998; Xiao and Tao, 2016). Therefore, the climate change and SD adjustment must exert effects on wheat yield (Xiao *et al*., 2016). However, the impacts of these two factors (climate change and SD adjustment) on spring wheat yield in NC are less reported.

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There are some approaches to assess the impacts of climatic variables and various agronomic management on crop yield (Lobell *et al.*, 2011; Xiao and Tao, 2014, 2016). Although laboratory experiments (or field experiments) could capture the impacts of these factors (i.e., climate, soil, water, cultivar and management) on crop productivity (Tao *et al.*, 2017), crop mechanism models, which fully consider the complex interactions between climate/weather conditions, soil properties, and agronomic managements that influence crop growth, could been used to simulate experimental results for a range of environmental conditions (Xiao and Tao, 2014; Wilcox and Makowski, 2014; Ewert *et al.*, 2015). Therefore, simulated models with demonstrated reliability and accuracy provide an alternative approach of assessing the impacts of different factors on crop growth and productivity with less time requirements and cost (Jones *et al.*, 2003). The APSIM modeling was selected in this study, because it is one of the most appropriate models widely used in Australia, Netherlands, India, Pakistan, North Africa, the USA, China, and also elsewhere around the globe (Mohanty *et al.*, 2012; Luo and Kathuria, 2013; Ahmed *et al.*, 2014, 2016; Ahmad *et al.*, 2015; Kouadio *et al.*, 2015; Kisaka *et al.*, 2016).

In this present study, based on the field-observed experiments data at six stations in the NC region, together with APSIM–Wheat model, the main objectives were to assess (1) the impacts of the change in important climate variables (i.e., temperature, solar radiation, and precipitation) on spring wheat yield and (2) the impacts of sowing date adjustment on spring wheat yield in NC region.

Materials and Methods

Study Area and Weather/Crop Data

This study area is located in the Northern China (NC), which is the main spring wheat production zone in China (Fig. 1). The six national agro-meteorological stations which used to conduct experiments and collect data in this present study included Zhangbei in Hebei province (HB), Guyang in Inner Mongolia Autonomous Region (IMG), Pingluo in Ningxia Autonomous Region (NX), Wuwei in Gansu province (GS), Haixi in Qinhai province (QH) and Hami in Xin jiang Autonomous Region (XJ) (Fig. 1). General information on the crops and stations in this study is summarized in Table 1. All the selected stations are located in typical spring wheat growing areas in China.

Daily whether data (i.e. maximum (Tmax) and minimum temperature (T_{min}), precipitation and sunshine hours) for 1981–2010 for the six selected stations were applied and acquired from the Chinese Meteorological Administration (CMA). Moreover, daily solar radiation for the six representative stations was computed from sunshine hours by the Angstrom–Prescott equation (Prescott, 1940; Xiao *et al.*, 2013). Records for cultivar type, phenology (i.e. sowing date (SD), anthesis date (AD) and maturity date

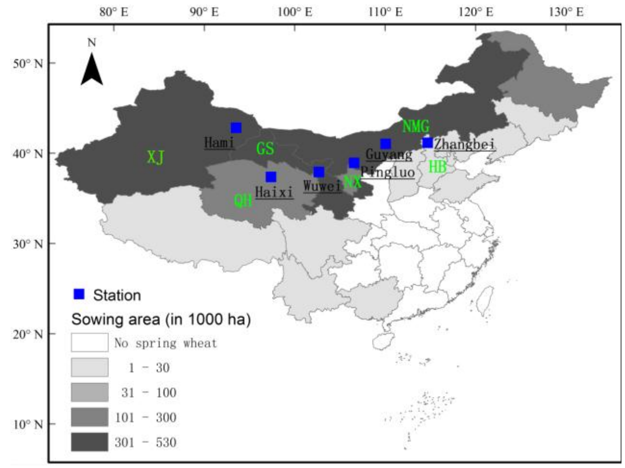

Fig. 1: Map of China depicting the locations of the agro-meteorological experimental stations where data were collected for the study

(MD), biomass and grain yield, and management practices for 1981–2010 were obtained from field-observed experiments conducted at the six selected stations. Generally, crop management measures at the six representative stations were the similar as the local traditional management measures. Irrigation and fertilizers were repeated used during the spring wheat growth seasons. Except Zhangbei and Guyang station where kept rain-fed conditions, irrigation generally was conducted 6–8 times at the other four stations during each growing season. Fertilizers were applied two times per year for the irrigated spring wheat, while only once fertilization at sowing time for rain-fed condition.

APSIM-Wheat Model Description

APSIM v7.4 was used in this study. APSIM model, as a cropping systems model, is developed by the agricultural production systems research unit of Australia. Due to this model is a component-driven model, it could concurrently runs some modules (e.g. crop growth/development processes and soil water/nitrogen dynamics). APSIM could simulates crop phonological stages, LAI (leaf area index), and biomass accumulation and partitioning as well as daily growths of root/stem/leaf and grain for the whole growth processes. In its genetic module for different crop, APSIM uses several genetic parameters related to the duration of each growth stage/phase, grain-filling rate, grain size and also photoperiod sensitivity (Holzworth *et al.*, 2014). APSIM model requires weather date (i.e., radiation, T_{max}, T_{min} and precipitation) in daily time-step and soil hydraulic parameter as input to drive the model. In this study, the typically spring wheat cultivars cultivated during the 1990–2006 in each of the six stations were selected used (Table 1). Then, we used the field observations (phenology and yield) during this period to calibrate and subsequently validate the

Table 1: General information of the stations and crop/climate data in six investigated stations in the Northern China

Station	Zhangbei	Guyang	Pingluo	Wuwei	Haixi	Hami
Province	Hebei	Neimenggu	Ningxia	Gansu	Qinghai	Xinjiang
Latitude (°N)	41.15	41.03	38.92	37.92	37.37	42.82
Longitude (°E)	114.70	110.05	106.55	102.67	97.37	93.52
Altitude (m)	1393.3	1360.4	1099.0	1530.8	2981.5	737.9
Crop data						
Period of crop data	1990–1998	1991–2001	1996–2006	1990–2001	1994–2004	1991–2001
Cultivar	Yulan	Xiaohongpi	Yongliang4	Yongliang4	Abo	Hachun1
Mean sowing date (DOY)	112 (22 Apr)	112 (22 Apr)	63 (4 Mar)	77 (18 Mar)	92 (2 Apr)	80 (21 Mar)
Mean anthesis date (DOY)	190 (9 Jul)	193 (12 Jul)	160 (9 Jun)	163 (12 Jun)	194 (13 Jul)	162 (11 Jun)
Mean maturity date (DOY)	226 (14 Aug)	228 (16 Aug)	192 (11 Jul)	200 (19 Jul)	240 (28 Aug)	197 (16 Jul)
Mean yield (kg ha^{-1})	1421.2	686.4	4794.0	6266.2	6422.7	5209.9
Climate data						
Period of weather data	1981–2010	1981–2010	1981–2010	1981–2010	1981–2010	1981–2010
Annual mean temperature (°C)	3.7	4.7	9.0	8.5	4.4	10.3
Annual mean solar radiation (MJ m^{-2})	15.1	16.2	16.8	16.3	18.2	17.0
Annual total precipitation (mm)	377.1	249.4	167.7	170.8	199.3	42.7
Management						
Irrigation	Rain fed	Rain fed	Irrigation	Irrigation	Irrigation	Irrigation
Fertilizer	Chemical fertilizer (N, P, K)	Chemical fertilizer (N, P, K)	Chemical fertilizer (N, P, K)	Chemical fertilizer (N, P, K)	Chemical fertilizer (N, P, K)	Chemical fertilizer (N, P, K)

Table 2: Detailed weather data used in APSIM–Wheat model simulation of the impact of climatic variables on wheat yield in Northern China

Climate variable	Temperature	Radiation	Precipitation
I_{all}	1981–2010	1981–2010	1981–2010
I_{temp}	1981–2010	Repeat of single year	Repeat of single year
I_{rad}	Repeat of single year	1981–2010	Repeat of single year
I_{prec}	Repeat of single year	Repeat of single year	1981–2010

Note that I_{all}, I_{temp}, I_{rad} and I_{prec} denote the estimated impacts of all climatic variables, temperature and solar radiation on spring wheat yield, respectively

APSIM–Wheat model. Generally, about 3 years of field-observed data were used to calibrate the model and the remaining years (about 5–8 years) of field-observed data were used to validate of the APSIM model.

The model performances were evaluated using several parameters, including slope, root mean square error (*RMSE*), coefficient of determination (R^2), and also agreement index (d) (Willmott, 1982) of observed and simulated values.

$$d = 1 - [\sum_{i=1}^{N} (P_i - O_i)^2 / \sum_{i=1}^{N} (|P_i^{'}| - |O_i^{'}|)^2]$$

$$0 \le d \le 1 \quad (1)$$

Where P_i was simulated values; O_i was observed values; N was number of values; and $P_i^{'} = P_i - \overline{O}$ and $O_i^{'} = O_i - \overline{O}$, $\overline{O}$ was the average observe value.

Methods

Time trends (1981–2010) in the climate variables (e.g., radiation, T_{max}, T_{min} and precipitation) at whole year and growth season of spring wheat in the six selected stations were determined by the linear regression model. In this study, the statistical significance of these trends was assessed using the two-tailed *t*-test analysis.

Furthermore, the four data-driven simulation groups were run to assess the impacts of the trends in climate variable (temperature, radiation and precipitation) on spring wheat yield during the 1981–2010 (Table 2). To assess the effect of a given climate variable (i.e., temperature) on yield of spring wheat, a 30 year simulation for 1981–2010 was run 30 times. In each 30 year simulation, daily observed data for the given variable (i.e., temperature) during 1981–2010 were used and daily data for the other input variables (e.g., radiation and precipitation) held constant for a given year (e.g., 1981) (Table 2). This resulted in 30 (daily temperature data of 1981–2010) × 30 (daily radiation and precipitation data for each year in 1981–2010), giving 900 simulation results. At last, the impact of the trends in each climate variable (e.g., temperature, radiation and precipitation) on spring wheat yield was estimated by calculating the trend in simulated mean spring wheat yield for 1981–2010.

To assess the impacts of SD adjustments on spring wheat yield, we conducted a control run of the model (ConM) using observed weather data during 1981 to 2010 based on the average SD during this period. Then, we ran the APSIM–Wheat model using the observed weather data during the period of 1981 to 2010, but with different SD. We set six simulation groups with different SD, which are SD advance 30 days (-30 d), 20 days (-20 d) and 10 days (-10 d), and also SD delay 10 days (+10 d), 20 days (+20 d) and 30 days (+30 d). Finally, the results of six groups of model run (i.e., -30 d, -20 d, -10 d, +10 d, +20 d and +30 d) were compared with that of ConM.

Results

APSIM–Wheat Model Calibration and Validation

The APSIM–Wheat model was calibrated and validated using the field-observed data from the six representative stations. These genetic parameters for cultivars-specific spring wheat that the model required were listed in Table 3. As shown in (Fig. 2a and b) the field-observed and model-simulated AD and MD closely agreed for the six representative stations. On average, the differences between observed and simulated AD and MD were less than 5 days. As shown in Table 4, R^2 and *d* values for the simulated wheat AD and MD in each station exceeded 0.46 and 0.62, respectively. Also, overall, the simulated grain yield of spring wheat was closed well with the observed one (Fig. 2c). The average difference between observed and simulated spring wheat yields were less than 228 kg ha^{-1} under rain-fed conditions and 539 kg ha^{-1} under irrigated conditions. For the simulated spring wheat yield in each station, R^2 and *d* values exceeded 0.59 and 0.81, respectively (Table 4). Based on the above results, the simulation of the APSIM model for spring wheat phenology and yield in NC were reliable and thus applicable.

Impacts of Climate Variable on Spring Wheat Yield

A significant warming trends were noted throughout the whole year and growth season of spring wheat in the 1981–2010 in all the six selected stations. The magnitude of increase temperature during annual period was greater than that during spring wheat growth period at the Zhangbei, Guyang and Haixi stations, the results of the other stations (Pingluo, Wuwei and Hami station) were just opposite (Table 5). Moreover, the magnitudes of rising in T_{min} were higher than that in T_{max} at the Zhangbei, Guyang and Wuwei stations. On the contrary, the rates of rising in T_{min} were smaller than that in T_{max} at Pingluo and Hami stations (Table 5). Radiation decreased at Zhangbei, Guyang and Haixi stations, with significant trend ($p<0.01$) at Zhangbei and Haixi stations. The magnitude of the decrease in radiation at the whole year was smaller than that at the seasonal cycle (spring wheat growth season). The radiation, however, increased at Pingluo, Wuwei and Hamxi stations, with a significant trend ($p<0.05$) at Wuwei and Hami stations. Moreover, the magnitude of increase in radiation during whole the year was smaller than that at spring wheat growth season cycle. During 1981–2010, precipitation was no significant trend ($p>0.05$) at the all investigated stations except Haixi station where precipitation rose significantly ($p<0.05$) at the annual cycle (Table 5).

The impact of the climate changes (also of the change in each climatic variable such as temperature, radiation and precipitation) on spring wheat yield for 1981–2010 was presented in Table 6. With temperature increasing during spring wheat growth period, yield decreased at all the selected stations except Haixi, with a significant trend ($p<0.05$) at Pingluo, Wuwei and Hami stations (Table 6). As shown in Table 6, Warming trends in the past 30 years decreased spring wheat yield at Zhangbei, Guyang, Pingluo, Wuwu and Hami by 0.2–1.1% yr^{-1}, however increased it at Haixi station by 0.3% yr^{-1}.

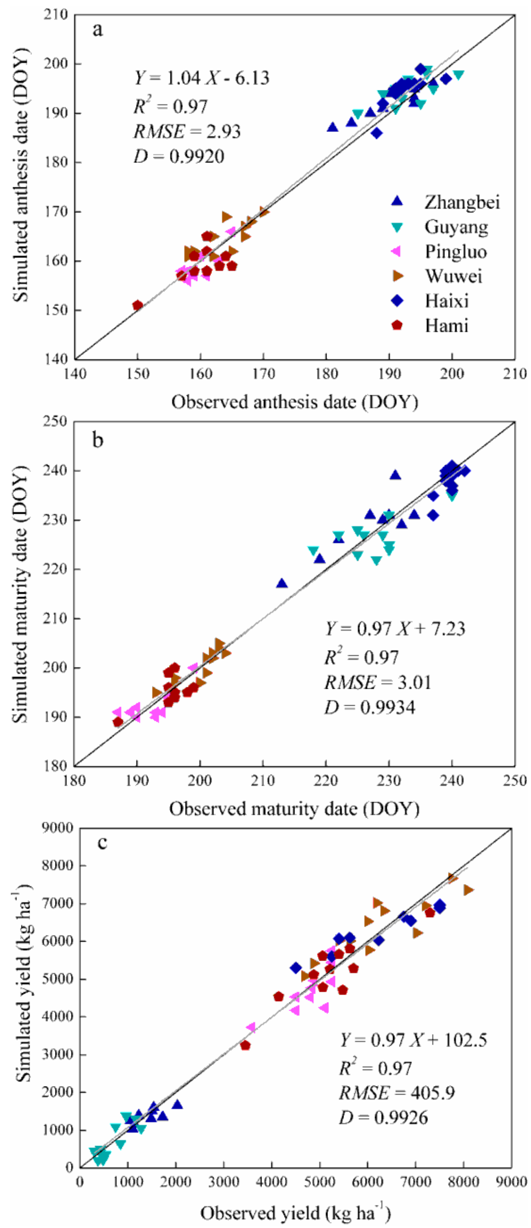

Fig. 2: Plot of the results of the APSIM–Wheat model validation analysis for the dates of anthesis and maturity, and yield at different stations in the study area

In the past 30 years, the trends of radiation are not consistent at the different stations (Table 5). Decrease in radiation reduced the wheat yield by 0.1% yr^{-1} at Zhangbei station, while it enhanced yield by 0.1% yr^{-1} at Guyang and Haixi station (Table 6). In contrast, increase in radiation

Table 3: Parameter values of spring wheat used in the APSIM–Wheat model simulation

Parameter	Station					
	Zhangbei	Guyang	Pingluo	Wuwei	Haixi	Hami
Emerg_to_endjuv (thermal time from emergence to end juvenile stage (° d))	450	580	530	460	520	560
Startgf_to_mat (thermal time from beginning of grain-filling to maturity (°d))	490	600	580	600	610	640
Potential_gain_filling_rate (potential grain-filling rate (g per kernel per day))	0.0020	0.0020	0.0023	0.0024	0.0025	0.0024
Grains_per_gram_stem (coefficient of kernel number per stem weight at the beginning of grain-filling (g per stem))	23.0	23.0	24.0	24.0	24.0	24.0
Max_grain_size (potential maximum grain size (g per kernel))	0.043	0.043	0.045	0.045	0.045	0.045
Phyllochron (phellochron interval (°C d/leaf appearance))	85	85	85	85	85	85
Photop_sens (sensitivity to photoperiod)	2.0	2.0	2.0	2.0	2.0	2.0

Table 4: The coefficient of determination (R^2), agreement index (*d*), and root mean square error (*RMSE*) of observed and simulated anthesis and maturity date and yield in six investigated stations in the Northern China

Station	Anthesis date			Maturity date			Yield		
	RMSE	R^2	*d*	*RMSE*	R^2	*d*	*RMSE*	R^2	*d*
Zhangbei	3.13	0.85	0.8461	3.95	0.84	0.8964	209.2	0.59	0.8166
Guyang	3.28	0.50	0.7870	4.29	0.57	0.7790	227.9	0.71	0.8959
Pingluo	2.30	0.55	0.8002	2.28	0.56	0.8560	367.3	0.62	0.8752
Wuwei	2.86	0.62	0.8414	1.68	0.82	0.9431	538.8	0.76	0.9050
Haixi	2.97	0.59	0.7760	2.59	0.52	0.6263	517.3	0.95	0.8924
Hami	2.92	0.50	0.8290	2.65	0.46	0.7741	404.8	0.81	0.9458

Table 5: Trends in solar radiation, maximum temperature (Tmax), minimum temperature (Tmin), and precipitation at annual and seasonal (wheat growth season) cycles in six investigated stations in the Northern China during the period of 1981–2010

Station	Period	Tmax		Tmin		Radiation		Precipitation	
		Mean (°C)	Trend (°C $10yr^{-1}$)	Mean (°C)	Trend (°C $10yr^{-1}$)	Mean (MJ m^{-2})	Trend (MJ m^{-2} $10yr^{-1}$)	Mean (mm)	Trend (mm $10yr^{-1}$)
Zhangbei	Annual	10.2	0.6**	-2.2	0.8**	15.1	-0.4**	377.1	-3.9
	Spring wheat growth period	22.0	0.4*	9.6	0.5**	20.7	-0.6**	246.7	-9.4
Guyang	Annual	12.0	0.6**	-1.6	0.7**	16.2	-0.2	249.4	-3.4
	Spring wheat growth period	24.6	0.4*	10.9	0.6**	22.2	-0.5	158.3	-1.8
Pingluo	Annual	16.4	0.6**	2.7	0.7**	16.8	0.1	167.7	17.7
	Spring wheat growth period	22.0	0.8**	7.6	0.7**	21.3	0.1	65.3	6.1
Wuwei	Annual	15.8	0.6**	2.0	0.9**	16.3	0.3*	170.8	7.0
	Spring wheat growth period	22.5	0.9**	8.1	1.1**	20.7	0.7**	74.3	-5.7
Haixi	Annual	11.6	0.6**	-1.3	0.7**	18.2	-0.3**	199.3	22.8*
	Spring wheat growth period	19.8	0.6**	7.1	0.6**	23.2	-0.4**	151.2	10.2
Hami	Annual	18.3	0.5**	3.3	0.1	17.0	0.2*	42.7	4.6
	Spring wheat growth period	27.5	0.7**	11.6	0.5**	23.4	0.5**	16.4	1.2

Note that single asterisk (*) denotes significant trend at the 5% probability level and double asterisks (**) denote significant trend at the 1% probability level

Table 6: Impacts of the trends in all climatic variables, in temperature, in radiation and in precipitation on spring wheat yields (kg ha^{-1} $year^{-1}$) in the Northern China during the period of 1981–2010

Variable	Zhangbei	Guyang	Pingluo	Wuwei	Haixi	Hami
I_{all}	-2.1(-0.1%)	-1.6(-0.2%)	-63.2**(-1.4%)	-10.2(-0.2%)	12.4(0.2%)	-30.7**(-0.6%)
I_{temp}	-3.0(-0.2%)	-2.1(-0.3%)	-53.4**(-1.1%)	-19.9*(-0.3%)	21.0**(0.3%)	-35.9**(-0.7%)
I_{rad}	-1.6(-0.1%)	0.4(0.1%)	-39.5**(-0.7%)	10.5(0.2%)	4.1(0.1%)	-9.0(-0.2%)
I_{prec}	-0.5(-0.1%)	-1.2(-0.2%)	4.3(0.1%)	-3.3(0.1%)	16.6(0.2%)	-7.2(-0.1%)

Note that the numbers in circle are values translated into percentage, single asterisk (*) denotes significant trend at the 5% probability level and double asterisks (**) denote significant trend at the 1% probability level. Also I_{all}, I_{temp}, I_{rad} and I_{prec} denote the estimated impacts of all climatic variables, temperature and solar radiation on spring wheat yield, respectively

reduced yield at Pingluo and Hami stations by 0.7% and 0.1% yr^{-1} respectively, while increase in radiation enhanced yield at Wuwei station by 0.2% yr^{-1} (Table 6). As shown in Table 6, decrease in precipitation reduced yield at Zhangbei, Guyang and Wuwei stations, and increase in precipitation enhanced yield at Pingluo and Haixi stations. As a result, the combined impacts of the changes in all the climatic variables in 1981–2010 reduce spring wheat yield at all the selected stations except Haixi, with a significant trend ($p<0.01$) at Pingluo and Hami station (Table 6).

Impacts of Sowing Date on Spring Wheat Yield

In the last three decades, the SD of spring wheat in NC changed dramatically (Xiao *et al*., 2016). In this study, six modeling experiments (different sowing date) were used to investigated the impacts of SD adjustment on wheat yield in NC. As shown in Fig. 3, for the rain-fed conditions in Zhangbei and Guyang stations, delayed SD slightly increased yield. However, advanced SD increased spring wheat yield at Pingluo, Wuwei, Haixi and Hami stations, all that under the irrigated condition (Fig. 3). All the results indicated that SD adjustment has certain influence on the spring wheat yield in NC. However, due to different water conditions (irrigated or rain-fed), the impacts were different.

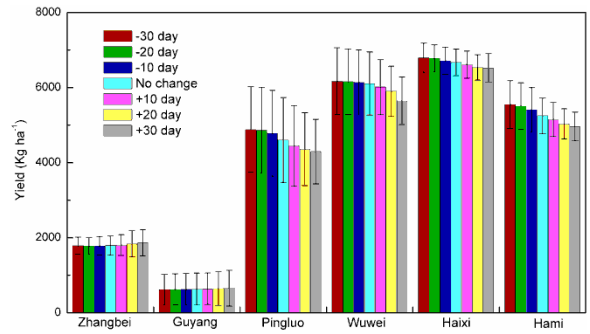

Fig. 3: Simulated yields of spring wheat under the different sowing date in the six investigated stations in northern China. The *error bar* is the 95% confidence interval

Discussion

Under the background of global warming, both of T_{max} and T_{min} increased significantly during the past three decades (1981–2010) in NC (Xiao *et al*., 2016). However, radiation has no consistent trend in the all selected stations. While radiation decreased in three stations, the other three stations have shown increased trends. During the past 30 years, the trends in precipitation during the spring wheat growing period were insignificant. The change of climate variables during the 1981–2010 exerted great effect on wheat growth and production in the region (Xiao *et al*., 2016). Due to the different climate/weather conditions at the different stations, the effects of the trends in climate variables on spring wheat yield were also different. Overall, climate change during the past three decades in NC exerted negative impacts on spring wheat yield at the most selected stations.

This study also indicated that the rise in temperature exerted a negative impact on spring wheat yield in the most of investigated stations. However, at the Haixi station, the increase in temperature enhanced spring wheat yield. The main reason was that the temperature during spring wheat growth period at Haixi was lower than that at the other investigated stations. While, the average T_{max} and T_{min} at the all investigated stations except Haixi was 22.0–27.5°C and 7.6–11.6°C, respectively, the average T_{max} and T_{min} at Haixi was only 19.8°C and 7.1°C, respectively. These results suggest that the temperature at the all investigated stations except Haixi has gone beyond the optimum temperature of the spring wheat growth in NC. Generally, warmer climate could accelerate crop growth/development and thereby shorten the length of the crop growth processes, and eventually exerted negative impact on yield (Xiao *et al*., 2013, 2016; Welch *et al*., 2010).

Previous studies showed that the decrease in radiation over the last several decades has significantly negative impact on the growth and productivity of winter wheat in the North China Plain (Xiao and Tao, 2014; Liu *et al*., 2016b). However, in this study, the decrease in radiation did not exert negative impact on the yield of spring wheat in NC. The results showed that decrease in radiation enhanced yield at Guyang and Haixi stations. On the contrary, the rise of radiation significantly reduced the spring wheat yield at Pingluo and Hami stations. Therefore, our findings have important implications that radiation is not the main limit factor for spring wheat growth and productivity at the most stations in NC region. In the other hand, increase in radiation trend to enhance crop evaporation, and further lead to crop water stress (Sauer *et al*., 2007; Li *et al*., 2010). As a result, higher radiation, to some extent, has negative impact on spring wheat yield in the NC.

During the last 30 years, there were no significantly trend in precipitation in NC. Therefore, the impact of precipitation on spring wheat yield is slight and insignificant. Under rain-fed condition, insignificant decrease in precipitation slightly reduce yield of wheat. Under irrigated condition, increase in precipitation slightly enhanced the spring wheat yield in Pingluo and Haixi stations. However, due to the little amount of precipitation in Hami (only 16.4 mm during the growth reason of spring wheat) and water requirement mainly relying on irrigation, slight increase in precipitation did not bring the increase of yield.

Shift in SD, to some extent, influence the time and durations of crop growth stage (Cirilo and Andrade, 1994; Zia-ul-hassan *et al*., 2014). Also, and again to a certain extent, shift in SD change the weather conditions in crop growth process (Dharmarathna *et al*., 2014; Xiao *et al*., 2016). Previous studies found that when SD of spring wheat in NC advancement reached 4 day $(10\ yr)^{-1}$, mean temperature of vegetative growth period (*VGP*) and whole growth period (*WGP*) decreased under warming climatic condition (Xiao *et al*., 2016). Therefore, SD changes eventually exert impacts on the yield of spring wheat. In our study, the impacts of changes in SD on spring wheat yield are different in the different water conditions (rain-fed and irrigated). Under rain-fed conditions, delay in SD will slightly enhanced spring wheat yield due to the water condition will be improved with the delay of wheat growing season. However, under irrigated conditions, advance in SD will increase yield of spring wheat. The main reason is that SD advancement decreases the temperature condition in the growth process of spring wheat in NC. Therefore, advance in SD, to some extent, mitigated and adapted to the ongoing climate change for spring wheat under the irrigated condition (Xiao *et al*., 2016).

Conclusion

This study used field-observed data from six CMA agro-meteorology stations along with APSIM–Wheat model simulation to assess the impacts of climate variables (i.e. temperature, radiation and precipitation) and sowing date on spring wheat yield in NC during the period of 1981–2010. We found that climate change mainly exerted negative impacts on spring wheat yield in the study region during the 30 year. The changes of temperature have gone beyond the optimum temperature of the spring wheat growth at the most investigated stations. However, the radiation is not the main limit factor for spring wheat growth and productivity in NC region. Moreover, the impacts of precipitation change on spring wheat yield were slight and insignificant during the study period. In addition, the impacts of SD adjustment on spring wheat yield are different in the different water conditions (rain-fed or irrigated). All the findings of this study could be useful in developing strategies to mitigate and adapt the impact of climate change on wheat production in the study area, as well as strengthen food security and promote social stability.

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