Modeling the sensitivity of wheat yield and yield gap to temperature change with two contrasting methods in the North China Plain

Huiqing Bai[1] · Jing Wang[1] · Quanxiao Fang[2,3] · Hong Yin[4]

Abstract

Wheat productivity in the North China Plain (NCP) is highly sensitive to climate change and varies greatly in spatial-temporal scale. Contrasting responses of wheat productivity to climate change were reported with different assessment methods. In this study, the impacts of climate warming (+ 2 °C) on wheat yields and yield gaps in the NCP were compared under rainfed, irrigated, and potential conditions using climatic resource utilization model (CRUM) and APSIM. Average potential yield increased 289 kg ha^{-1} per decade ($P < 0.01$) simulated by CRUM but decreased 219 kg ha^{-1} per decade ($P < 0.01$) simulated by APSIM across the NCP during 1961–2010. Under the + 2 °C scenario compared with current climate (1961–2010), wheat yields under potential, two irrigations, one irrigation, and rainfed conditions increased 27%, 23%, 28%, and 13% simulated by CRUM but decreased 7%, 8%, 10%, and 17% simulated by APSIM. Simulated yield gaps between potential yield and yields under rainfed and one and two irrigations by CRUM increased 33%, 27%, and 32%, respectively. Simulated yield gap between potential and rainfed yields by APSIM increased 9% while the gaps between potential yield and yields under one and two irrigations by APSIM decreased 12% and 10%. Without cultivar change, simulated shortened growth period by APSIM due to increased temperature would decrease wheat yields. By contrast, increased temperature under a constant growth period assumed by CRUM would increase yields especially potential yield. This suggested that wheat yields could be maintained by effective utilization of crop growth duration, such as breeding new cultivars under warming climate in the NCP.

✉ Jing Wang
   wangj@cau.edu.cn

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

[2] Agronomy College, Qingdao Agricultural University, Qingdao 266109, China

[3] Institute of Soil and Water Conservation, Chinese Academy of Sciences, Ministry of Water Resources, Yangling 712100, China

[4] National Climate Center, China Meteorological Administration, Beijing 100081, China

1 Introduction

Wheat, one of the staple cereal crops worldwide, accounts for approximately 11% of the total planting area and more than 17% of the total grain yield in China (FAO 2013). As the largest wheat production region in China, the North China Plain (NCP) which implements irrigation extensively produces about two-thirds of the total wheat yield and supplies 50% of the nation's wheat grain (Wang et al. 2012). Therefore, it plays a key role in securing national food supply in China. It is known that most wheat varieties require both a relatively cool climate in the early growing season and a cold temperature in a minimum period to trigger reproductive development (Porter and Gawith 1999). However, observed data showed that climate warming has been accelerated since 1980s and a higher increase in temperature has even been projected in the future (Ding et al. 2006; Tao et al. 2006; Wang et al. 2018). Wheat production in the NCP has been facing a great challenge in adapting to climate change (Piao et al. 2010; Wang et al. 2012). Previous simulation studies showed that climate warming would result in a decline in wheat yield (Tao et al. 2006; Chen et al. 2010b; Wang et al. 2012). However, observed wheat yield has been increasing from 1960s in the NCP suggesting effective adaptation to climate change (Xu and Zhao 2001; Zhang et al. 2005; Sun et al. 2007; Zhou et al. 2007; Wang et al. 2012). Recent meta-analysis of the impacts of future climate change on grain yield concluded that without adaptation, a warming of 2 °C would produce negative impacts on wheat yield although some regions were found to be benefit from climate change (Porter et al. 2014). Therefore, understanding the adaption potential and unraveling the relative contributions of different adaptation options are of importance in developing future adaption strategies.

Two types of approaches including crop growth models, such as APSIM (Keating et al. 2003), WOFOST (Diepen et al. 1989), and CERES (Jones and Kiniry 1986), and climatic resource utilization models (CRUM) (He et al. 2014, 2017b; Tang et al. 2016) were widely used to assess the impact of climate change on crop yield. A common difference of two methods was that crop growth model was mainly to represent key dynamic processes affecting crop yield and require a large number of soil and crop parameters (He et al. 2017a), while CRUM used a relatively simple method to conduct the relationships between crop yield and climate factors (He et al. 2017b). In general, previous studies based on crop growth models found that past and future climate change decreased wheat yield if without adaptation in the NCP (Zhang et al. 2006; Cong et al. 2008; Chen et al. 2013; Li et al. 2014). In addition, the yield gaps between potential and rainfed yields showed an increasing trend in the NCP due to more significant decrease in rainfed yield than potential yield (Li et al. 2012). However, climate change had positive impacts on wheat yield in the NCP based on the assessments with climatic resource utilization models (Wang et al. 2010a; Zhao et al. 2011). The opposite simulation results by two types of models suggested a large difference in response of wheat growth to climate change. The difference would lead to contrasting conclusions in identifying climate change impacts and developing adaption strategy to future climate change under different agronomic management practices. Therefore, understanding the difference in response mechanism to climate change between two types of models could help quantify the climate change impact accurately and reveal the adaptation potential by breeding and management strategies.

Moreover, previous climate change impact studies focused on two extreme conditions, i.e., potential and rainfed; however, winter wheat was usually irrigated one to two times in the NCP (Fang et al. 2010). Therefore, it is essential to understand the adaptation potential of wheat production in past and future climate change under different irrigation management conditions, which was few investigated in the NCP (Li et al. 2012). The objectives of this study were to

quantify the sensitivity of changes in simulated potential, irrigated, and rainfed yields of winter wheat, and their yield gaps to climate warming in the NCP with two contrasting methods (i.e., APSIM and CRUM) under current climate (1961–2010) and future climate warming scenario (+ 2 °C), and the climate warming effect on wheat yields and yield gaps was particularly investigated using the two different methods.

2 Materials and methods

2.1 Climate, study sites, and wheat-growing districts

Forty-three representative meteorological sites were selected in the NCP including Hebei, Henan, and Shandong provinces and Beijing and Tianjin municipalities except the northern Hebei province, where spring wheat was grown (Fig. 1). Historical daily weather data from 1961 to 2010 were available from China Meteorological Administration, including sunshine hours (h), daily average, maximum and minimum temperatures (°C), precipitation (mm), wind speed (m s^{-1}), and relative humidity (%). Daily global solar radiation was estimated from sunshine hours based on the Angstrom equation (Wang et al. 2015). Winter wheat and summer maize rotation is the major crop system in the NCP. The region has experienced a significant decrease in global solar radiation and increase in air temperature during the past decades (Ding et al. 2006; Piao et al. 2010; Wang et al. 2012, 2015), while annual precipitation decreased in the north and increased in the southeast of NCP (Liu et al. 2005; Wang et al. 2008; Hu et al. 2013). Observed wheat phenology from 43 agro-meteorological sites in the NCP was selected to divide the wheat-growing districts with different sowing dates and growing periods (Fig. 1).
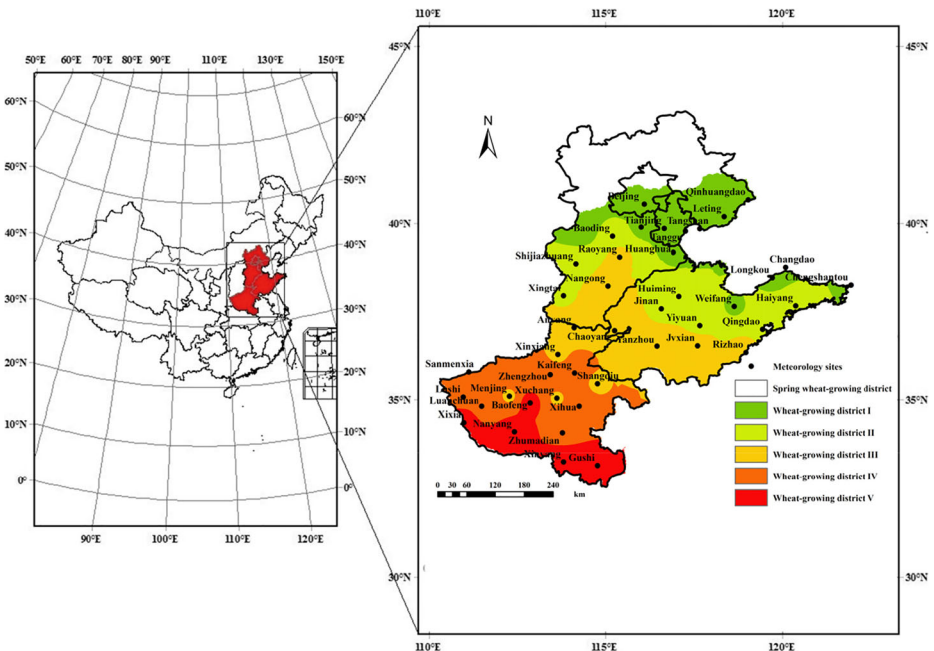

Fig. 1 North China Plain (NCP) and the distribution of the study sites

Average growing season solar radiation, average temperature, and precipitation in five wheat-growing districts ranged from 2654.5 to 2745.7 MJ m^{-2}, from 7.0 to 12.8 °C, and from 147 to 361 mm respectively in the NCP under current climate (1961–2010) (Fig. 2). The changes of average growing season solar radiation, average temperature, and precipitation in five wheat-growing districts ranged from − 49.8 to − 19.6 MJ m^{-2} per decade, from 0.26 to 0.43 °C per decade, and from − 8.8 to 0.7 mm per decade during 1961–2010.

2.2 Climate change impact assessment methods

2.2.1 APSIM model

APSIM model (version 7.7) was used to investigate the impact of climate change on wheat yield under potential, irrigated, and rainfed conditions under current climate (1961–2010) and future climate warming scenario (+ 2 °C). It has been well tested and widely used in the NCP (Chen et al. 2010a, 2010b; Zhang et al. 2012; Wang et al. 2013). Here, we used local wheat varieties in different wheat-growing districts with higher vernalization sensitivity in the district I (variety Jimai_22) and district II (variety Jining_142) and lower vernalization sensitivity in the district III-V (variety Zhengzhou_761) in reference to previous studies (Table 1, Li et al. 2016a, 2016b). The sowing depth and density of winter wheat were set as 40 mm and 400 plants m^{-2} respectively. Winter wheat was harvested at its physiological maturity date. Summer maize was planted in late June after harvesting winter wheat and harvested before sowing winter wheat. No nitrogen fertilizer stress occurred during the growing period of winter wheat and summer maize. Because 70% of annual precipitation is concentrated in the growing period of summer maize, no supplemental irrigation was applied during the growing period of summer maize (Wang et al. 2010b). All the simulation experiments were run continuously from 1961 to 2010, i.e., without resetting initial soil conditions at each sowing of winter wheat. Although the growth of summer maize would impact on soil water content before sowing winter wheat, continuous simulation could mimic actual production condition. Moreover, supplemental irrigation would apply before sowing winter wheat if soil water content in 150 cm depth was lower than 65% of the field capacity, which would alleviate the impact of previous crop on soil water content of winter wheat growth period.

In addition to daily meteorological data (maximum temperature, minimum temperature, precipitation and solar radiation), detailed soil data including the soil bulk density (BD, g cm^{-3}), saturated volumetric water content (SAT, mm mm^{-1}), drained upper limit (DUL, mm mm^{-1}), 15 Bar lower limit (LL15, mm mm^{-1}), soil organic carbon content (SOC, %), and pH
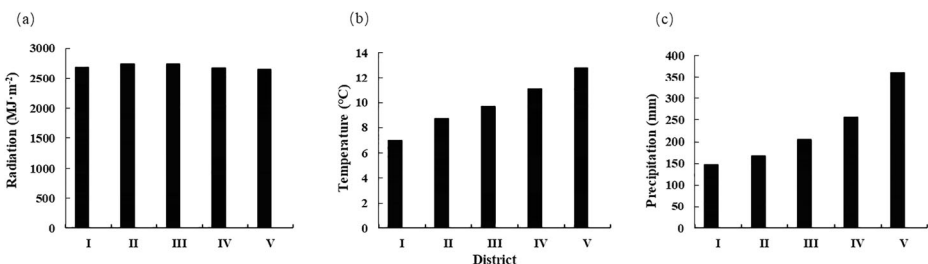

Fig. 2 Growing season total solar radiation (a), average temperature (b), and total precipitation (c) in different wheat-growing districts in the NCP averaged from 1961 to 2010

Table 1 Genetic parameters used in the APSIM for different wheat varieties in the NCP

Definition of parameters	Values		
	Jimai_22	Jining_142	Zhengzhou_761
vern_sens (sensitivity to vernalisation)	2.3	2.1	2.0
photo_sens (sensitivity to photoperiod)	3.5	3.9	2.5
startgf_to_mat (thermal time from beginning of grain-filling to maturity ($^\circ$C d))	610	570	520
grain_per_gram_stem (coefficient of kernel number per stem weight at the beginning of grain-filling (g per stem))	28.5	28.5	28.5
potential_grain_filling rate (potential grain-filling rate (g per kernel per day))	0.0035	0.0035	0.0035

The first two parameters determine the length of vegetative growth period of winter wheat while the third parameter determines the length of reproductive growth period of winter wheat. Therefore, higher sensitivity to vernalization and photoperiod suggests longer vegetative growth period while higher thermal time from beginning of grain-filling to maturity suggests longer reproductive growth period. The coefficient of kernel number per stem weight at the beginning of grain-filling reflects the potential kernel number per stem determined by stem weight at the beginning of grain-filling. Higher potential grain-filling rate reflects that the wheat variety has higher grain-filling capacity

value (pH) in different soil layers was obtained from the local agro-meteorological sites and the China Soil Scientific Database (http://www.soil.csdb.cn) were input into the APSIM.

In the APSIM, the phenological phases of winter wheat is determined by temperature together with the vernalization and photoperiod sensitivity of a target cultivar. Daily above-ground biomass accumulation was determined by daily solar radiation interception and radiation use efficiency (g MJ^{-1}), reduced by water and nitrogen stress. Grain yield was determined by grain number and daily grain-filling rate (Keating et al. 2003).

2.2.2 Climatic resource utilization model

Climatic resource utilization model calculated crop yield based on the estimated photosynthetic yield reduced by suboptimal temperature and water deficit (Huang 1985; He et al. 2014, 2017b). Contrasting with crop growth model, climatic resource utilization model was used to investigate the impact of climate change on wheat yields under potential, irrigated, and rainfed conditions assuming a constant growth period. Wheat-growing districts, sowing dates, and the lengths of five phenological stages in each district are shown in Table 2.

The potential yield (PY, 10^3 kg ha^{-1}) represents the maximum yield under stress-free condition and is determined by solar radiation and temperature:

Table 2 Sowing dates and the lengths (day) of five phenological stages of winter wheat in each wheat-growing district

District	Sowing date	Initial stage	Dormancy stage	Development stage	Middle stage	Late stage	Total
I	Oct 2	65	90	40	25	30	250
II	Oct 7	65	75	40	30	35	245
III	Oct 12	65	65	40	30	35	235
IV	Oct 17	65	55	35	35	35	225
V	Oct 22	75	45	30	35	35	220

$$PY = \sum_{j=1}^{5} \left(\sum_{i=1}^{gd_j} \left(0.219 \times C \times R_{s,i} \times f(T_i) \right) \right) \tag{1}$$

where 0.219 is the Bingwei Huang coefficient in unit of 10^{-5} kg kJ^{-1} (He et al. 2014), and C is the crop harvest index, taking the value of 0.56 for wheat (Qin et al. 2013a). j represents each phenological stage (initial, dormancy, development, middle and end of the wheat growth period), and gd_j is the length of each stage. $R_{s,i}$ is the daily solar radiation in unit of kJ cm^{-2} day^{-1}, calculated as

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

where $R_{a,i}$ is the daily extraterrestrial radiation in kJ cm^{-2} day^{-1}, n_i is the daily actual duration of sunshine in hours, and N_i is the daily maximum possible duration of sunshine in hours. $a_s = 0.25$ and $b_s = 0.50$ are used for the estimation of $R_{s,i}$.

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

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

where T_i is the daily average temperature which is the arithmetic mean value of the daily maximum and minimum temperatures (°C), and $T_{min,j}$, $T_{o,j}$, and $T_{max,j}$ are the minimum, optimum, and maximum temperatures (°C) for wheat growth in each of the phenological stages, respectively. The values of $T_{min,j}$, $T_{o,j}$, and $T_{max,j}$ (Table 3) were derived according to Porter and Gawith (1999).

The rainfed yield (RY, 10^3 kg ha^{-1}) represents the maximum yield that can be achieved under local rainfed condition and is calculated by correcting the yield determined by solar radiation and temperature with the water stress coefficient (He et al. 2014):

$$RY = \sum_{j=1}^{5} \left(\sum_{i=1}^{gd_j} \left(0.219 \times C \times R_{s,i} \times f(T_i) \right) \times f(W_j) \right) \tag{4}$$

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

$$f(W_j) = \begin{cases} P_j/ET_{c,j} & 0 \leq P_j < ET_{c,j} \\ 1 & P_j \geq ET_{c,j} \end{cases} \tag{5}$$

where P_j is the total precipitation during each phenological stage (mm). $ET_{c,j}$ is the total water requirement of wheat during each phenological stage (mm) which can be calculated as

Table 3 Minimum, optimum, and maximum temperatures (°C) for wheat growth and development during the five phenological stages

Phenological stages	T_{min}	T_o	T_{max}
Initial stage	3	18	35
Dormitory stage	0	24	30
Development stage	8	27	32
Middle stage	10	25	35
Late stage	10	18	35

$$ET_{c,j} = \sum_{i=1}^{gd_j}\left(ET_{0,i} \times K_{c,i}\right) \tag{6}$$

$K_{c,i}$ is the crop coefficient calculated by the single crop coefficient method, as recommended in Allen et al. (1998), based on the five threshold values of 0.7, 0.4, 1.15, 1.15, and 0.4 during the initial, dormancy, development, middle, and end of the wheat growth period, respectively. ET_0 is calculated by the FAO Penman–Monteith equation (Allen et al. 1998):

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

where $ET_{0,i}$ is the daily reference crop evapotranspiration in mm day^{-1}; R_n is the net radiation in MJ m^{-2} day^{-1}; G is the soil heat flux in MJ m^{-2} day^{-1}; T is the daily average temperature at 2-m height in °C; U_2 is the wind speed at 2-m height in m s^{-1}; e_s is the saturated water vapor pressure in kPa; e_a is the actual water vapor pressure in kPa; Δ is the slope of the saturation vapor pressure versus temperature relationship in kPa °C^{-1}; and γ is the psychrometric constant in kPa °C^{-1}. R_n is the difference between the incoming net shortwave radiation and the outgoing net long wave radiation. Wind speed measured at 10-m height was adjusted to 2-m height using a logarithmic wind speed profile. ET_0 was calculated in daily time steps, and G was negligible and assumed to be zero in this study (Allen et al. 1998).

2.3 Climate warming and irrigation scenarios

To simulate the impact of rising temperature on winter wheat yield, relative change in maximum and minimum temperatures (+ 2 °C) was used to represent future climate warming scenarios without the changes in other climate variables in reference to the target levels of 2 °C in the Paris Agreement (King et al. 2018). Because wheat production in the NCP was neither under potential nor under rainfed conditions due to limited available water resources, one to two times irrigations were usually applied during the growing season of winter wheat in the NCP (Fang et al. 2010). Considering the impact of the distribution of the precipitation during crop growth season on soil moisture, one irrigation with 75 mm would apply at jointing and two irrigations would apply at jointing and flowering with each 75 mm, respectively, if the soil water content in 150 cm depth exceeded 65% of the field capacity before sowing winter wheat. Otherwise, one irrigation with 75 mm would apply at sowing and two irrigations would apply at sowing and jointing with each 75 mm respectively. Therefore, two irrigation scenarios were used to investigate the interaction impacts of climate change and irrigation management practices on wheat productivity in the NCP.

To quantify the spatial-temporal changes in simulated potential, irrigated, and rainfed yields of winter wheat and their yield gaps in the NCP, two different models, APSIM and CRUM, were used as tools under current climate (1961–2010) and warming scenarios (+ 2 °C based on the current climate) with different irrigation conditions.

The yield gaps between simulated potential yield and yields under rainfed, one irrigation, and two irrigations conditions by both models were calculated:

$$YG_R = Y_P - Y_R \tag{8}$$

$$YG_I = Y_P - Y_I \tag{9}$$

$$YG_{II} = Y_P - Y_{II} \tag{10}$$

$$YG_{RW} = Y_{PW} - Y_{RW} \tag{11}$$

$$YG_{IW} = Y_{PW} - Y_{IW} \tag{12}$$

$$YG_{IIW} = Y_{PW} - Y_{IIW} \tag{13}$$

where Y_P is simulated potential yield under current climate. Y_R, Y_I, and Y_{II} were simulated yields under rainfed and one and two irrigations conditions respectively under current climate. YG_R, YG_I, and YG_{II} were simulated yield gaps between potential and rainfed yields, between potential yield and yield with one irrigation, and between potential yield and yield with two irrigations, respectively, under current climate. Y_{PW} is simulated potential yield under the scenarios + 2 °C. Y_{RW}, Y_{IW}, and Y_{IIW} were simulated yields under rainfed, one irrigation, and two irrigations conditions respectively under the scenarios + 2 °C. YG_{RW}, YG_{IW}, and YG_{IIW} were simulated yield gaps between potential and rainfed yields, between potential yield and yield with one irrigation, and between potential yield and yield with two irrigations, respectively, under the scenarios + 2 °C.

2.4 Data analysis

Linear regression was used to detect the change trends in the potential, irrigated, and rainfed yields of winter wheat under the current climate and warming climate scenario. The slope of the linear regression line against time was evaluated using Student's *t* test with confidence of 95% and 99% levels. The simulation results of potential, irrigated, and rainfed yields and their gaps at the site were spatially interpolated by applying inverse distance weighting (IDW) interpolation method (He et al. 2017b).

3 Results

3.1 Wheat yields and their gaps under current climate

Simulated Y_P, Y_{II}, Y_I, Y_R (i.e., potential, two irrigations, one irrigation and rainfed yields) by CRUM increased by 289, 149, 97, and 58 kg ha^{-1} per decade respectively during 1961–2010, and showed significant increases at 70%, 37%, 12%, and 12% of the study sites across the NCP respectively (Fig. 3a–d). However, simulated Y_P, Y_{II}, Y_I, and Y_R by APSIM decreased by 219, 129, 138, and 218 kg ha^{-1} per decade respectively during 1961 to 2010 and showed significant decreases at 79%, 30%, 28%, and 26% of the study sites across the NCP (Fig. 3e–h).

As shown in Table 4, significant positive correlation existed between simulated wheat yields by CRUM and growing season average temperature for the five wheat-growing districts (R^2 ranging from 0.61 to 0.80, 0.02 to 0.19, and 0.02 to 0.19 for Y_P, Y_{II}, and Y_I respectively). Therefore, rising growing season average temperature increased potential and irrigated yields
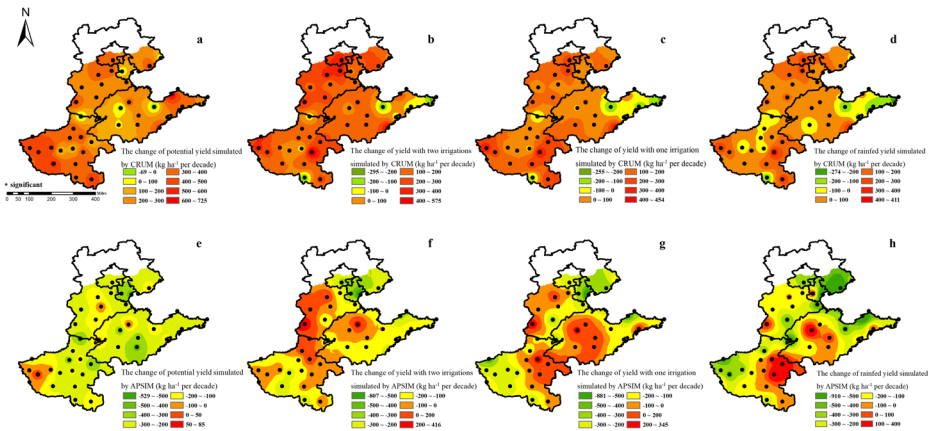
Fig. 3 Potential, irrigated, and rainfed wheat yield changes in the North China Plain simulated by climatic resource utilization model (CRUM) (**a–d**) and APSIM (**e–h**) under current climate (1961–2010)

of winter wheat during 1961–2010 as shown in Fig. 3a–d. There was a significant positive correlation between simulated wheat yields by CRUM and growing season precipitation for the five wheat-growing districts (R^2 ranging from 0.31–0.68, 0.38–0.58, and 0.53–0.72 for Y_{II}, Y_I, and Y_R respectively). However, significant negative correlation was found between simulated wheat potential yield by APSIM and growing season average temperature for the district II, III, and IV (R^2 ranging from 0.09–0.16). More significant positive correlation occurred between simulated potential yield of winter wheat by APSIM with growing season solar radiation with R^2 ranging from 0.45 to 0.65. Therefore, rising temperature and reduced solar radiation decreased potential yield of winter wheat during 1961 to 2010 (Fig. 3e–h). Similar to CRUM, simulated winter wheat yields by APSIM had a significant positive correlation with growing season precipitation (R^2 ranging from 0.06 to 0.63, 0.07 to 0.74, 0.15 to 0.43 for Y_{II}, Y_I, and Y_R, respectively).

Simulated YG_R, YG_I, and YG_{II} (i.e., yield gaps between potential yield and the yields under rainfed, one irrigation and two irrigations) by CRUM increased by 231, 202, and 139 kg ha^{-1} per decade respectively during 1961–2010 and showed significant increases at 30%, 26%, and 19% of the study sites across the NCP respectively (Fig. 4a–c). However, simulated YG_R, YG_I, and YG_{II} by APSIM decreased by 3, 80, and 156 kg ha^{-1} per decade respectively during 1961 to 2010 with significant decreases at 16%, 26%, and 28% of the study sites across the NCP (Fig. 4d–f). Both model simulations showed a positive effect of irrigation on the trends in wheat yield gaps from 1961 to 2010 in the region.

As shown in Table 5, simulated yield gaps by CRUM had a significant negative correlation with growing season precipitation (R^2 ranging from 0.34 to 0.48, 0.30 to 0.44, and 0.26 to 0.46 for YG_R, YG_I, and YG_{II} respectively). Significant positive correlation existed between simulated yield gaps by CRUM and growing season average temperature (R^2 ranging from 0.15 to 0.45, 0.10 to 0.46, and 0.10 to 0.40 for YG_R, YG_I, and YG_{II}, respectively) for five wheat-growing districts and growing season solar radiation (R^2 ranging from 0.06 to 0.14, 0.04 to 0.16, and 0.06 to 0.12 for YG_R, YG_I, and YG_{II}, respectively) for five wheat-growing districts except district II. Similarly, simulated yield gaps by APSIM had a significant negative correlation with growing season precipitation (R^2 ranging from 0.14 to 0.40, 0.15 to 0.43, and 0.07 to 0.46 for YG_R, YG_I, and YG_{II}, respectively) for five wheat-growing districts. Contrasting with CRUM, however, simulated yield gaps by APSIM had a significant negative

Table 4 The relationship between potential and rainfed yields simulated by climatic resource utilization model (CRUM) and APSIM and growing season solar radiation, average temperature, and precipitation in different wheat-growing districts in the NCP under current climate (1961–2010)

District	Model	Yield	Radiation		Temperature		Precipitation	
			Slope	R^2	Slope	R^2	Slope	R^2
I	CRUM	Y_P	3.29	0.07**	1057.7	0.61**	−5.07	0.04**
	APSIM		3.23	0.63**	51.05	0.001	4.70	0.12**
	CRUM	Y_{II}	0.21	0.0006	163.37	0.02**	14.77	0.63**
	APSIM		−0.26	0.0006	308.05	0.08**	15.46	0.63**
	CRUM	Y_I	−0.14	0.0002	338.12	0.11**	12.94	0.50**
	APSIM		−0.05	3E−05	160.65	0.02**	17.10	0.74**
	CRUM	Y_R	−0.55	0.004	53.42	0.003	14.87	0.69**
	APSIM		7.88	0.27**	334.7	0.004	30.46	0.35**
II	CRUM	Y_P	0.98	0.005	1306.7	0.73**	−6.12	0.07**
	APSIM		3.18	0.65**	−601.0	0.14**	5.97	0.16**
	CRUM	Y_{II}	−0.33	0.001	−20.88	0.0003	15.10	0.68**
	APSIM		3.67	0.12**	−38.47	8E-0.5	27.77	0.48**
	CRUM	Y_I	−0.90	0.009	172.65	0.02**	13.47	0.54**
	APSIM		3.18	0.12**	−211.1	0.003	25.33	0.52**
	CRUM	Y_R	−0.60	0.004	−53.25	0.002	15.87	0.71**
	APSIM		4.25	0.12**	130.7	0.0007	30.03	0.43**
III	CRUM	Y_P	0.40	0.002	995.3	0.62**	−1.31	0.006
	APSIM		2.17	0.53**	−532.3	0.16**	−0.29	0.0007
	CRUM	Y_{II}	−2.82	0.09**	545.4	0.19**	12.30	0.49**
	APSIM		0.30	0.002	184.5	0.003	16.88	0.35**
	CRUM	Y_I	−2.31	0.06**	274.6	0.05**	11.89	0.49**
	APSIM		0.49	0.003	168.5	0.0002	21.34	0.40**
	CRUM	Y_R	−2.67	0.08**	296.3	0.06**	13.87	0.68**
	APSIM		1.18	0.01	39.83	7E−05	23.52	0.37**
IV	CRUM	Y_P	3.94	0.08**	1360.2	0.70**	−2.12	0.01*
	APSIM		2.73	0.57**	−411.8	0.09**	−0.63	0.006
	CRUM	Y_{II}	−1.26	0.01	280.9	0.04**	9.08	0.31**
	APSIM		0.66	0.008	−162.3	0.003	4.27	0.06**
	CRUM	Y_I	−2.36	0.03**	272.6	0.03**	10.40	0.38**
	APSIM		−0.65	0.004	31.15	7E−05	10.02	0.18**
	CRUM	Y_R	−2.76	0.04**	39.63	0.0006	12.64	0.53**
	APSIM		−1.21	0.01	250.0	0.003	14.08	0.23**
V	CRUM	Y_P	5.12	0.14**	1590.8	0.80**	0.80	0.005
	APSIM		2.73	0.45**	−84.8	0.004	−1.09	0.04**
	CRUM	Y_{II}	−0.47	0.001	725.6	0.16**	8.64	0.53**
	APSIM		2.16	0.24**	47.0	0.0009	−0.05	7E−05
	CRUM	Y_I	−1.66	0.01	897.7	0.19**	10.22	0.58**
	APSIM		1.14	0.02	299.0	0.01	2.50	0.07**
	CRUM	Y_R	−1.77	0.01	647.7	0.10**	11.5	0.72**
	APSIM		0.09	7E−0.5	953.2	0.06	5.94	0.15**

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

correlation with growing season average temperature (R^2 ranging from 0.02 to 0.07, 0.02 to 0.03, and 0.02 to 0.05 for YG_R, YG_I, and YG_{II} respectively) for five wheat-growing districts. Simulated yield gaps by APSIM had a significant negative correlation with growing season solar radiation (R^2 ranging from 0.04 to 0.13) for wheat-growing district I while had a significant positive correlation with growing season solar radiation (R^2 ranging from 0.05 to 0.13, 0.03 to 0.11, and 0.04 to 0.06 for YG_R, YG_I, and YG_{II} respectively) for wheat-growing district III, IV, and V.
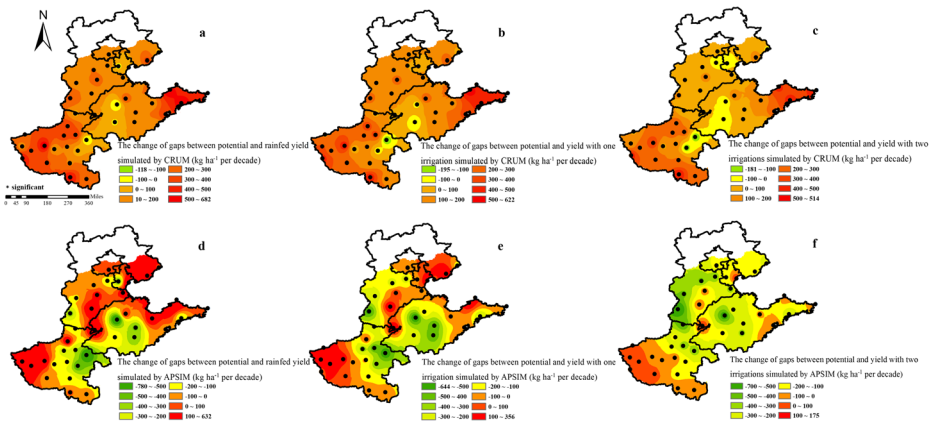
Fig. 4 Changes in the gaps between potential yield and the yields under rainfed and one and two irrigations in the North China Plain simulated by climatic resource utilization model (CRUM) (**a–c**) and APSIM (**d–f**) under current climate (1961–2010)

3.2 Potential, irrigated, and rainfed wheat yields and their gaps under climate warming

Under the scenario of rising temperature by 2 °C, simulated Y_{PW}, Y_{IIW}, Y_{IW}, and Y_{RW} (i.e., potential, two irrigations, one irrigation, and rainfed yields) by CRUM increased by 315, 134, 81, and 53 kg ha^{-1} per decade during 1961–2010 and showed significant increases at 67%, 30%, 12%, and 14% of the study sites across the NCP respectively (Fig. 5a–d). However, simulated Y_{PW}, Y_{IIW}, Y_{IW}, and Y_{RW} by APSIM decreased by 250, 136, 140, and 215 kg ha^{-1} per decade during 1961 to 2010 and showed significant decreases at 84%, 35%, 23%, and 26% of the study sites across the NCP, respectively (Fig. 5e–h). Simulated average Y_{PW}, Y_{IIW}, Y_{IW}, and Y_{RW} by CRUM increased by 2853 kg ha^{-1} (27%), 1089 kg ha^{-1} (23%), 1082 kg ha^{-1} (28%), and 409 kg ha^{-1} (13%), respectively, while simulated average Y_{PW}, Y_{IIW}, Y_{IW}, and Y_{RW} by APSIM decreased by 650 kg ha^{-1} (7%), 603 kg ha^{-1} (8%), 580 kg ha^{-1} (10%), and 781 kg ha^{-1} (17%), respectively, across the NCP under the +2 °C scenarios compared with the current climate (1961–2010). Consistent relationships between potential, irrigated, and rainfed yields simulated by CRUM and APSIM and growing season solar radiation, average temperature, and precipitation were found between the scenarios of +2 °C and current climate because of the same climate variability (data not shown).

Under the scenario of rising temperature by 2 °C, simulated yield gaps between potential yield and the yields under rainfed and one and two irrigations (YG_R, YG_I, YG_{II}) by CRUM increased by 258, 227, and 179 kg ha^{-1} per decade and showed significant increases at 33%, 30%, and 21% of the study sites across the NCP, respectively (Fig. 6a–c). However, simulated YG_R, YG_I, and YG_{II} by APSIM decreased by 35, 111, and 165 kg ha^{-1} per decade and showed significant decreases at 14%, 23%, and 35% of the study sites across the NCP, respectively (Fig. 6d–f). Simulated YG_R, YG_I, and YG_{II} by CRUM increased by 2443 kg ha^{-1} (33%), 1771 kg ha^{-1} (27%), and 1764 kg ha^{-1} (32%) respectively, and simulated YG_R increased by 134 kg ha^{-1} (9%) while simulated YG_I and YG_{II} by APSIM decreased by 72 kg ha^{-1} (12%) and 50 kg ha^{-1} (10%) respectively across the NCP under the +2 °C scenarios compared with

Table 5 The relationship of yield gaps between potential yield and the yields under rainfed, one irrigation, and two irrigations simulated by climatic resource utilization model (CRUM) and APSIM and growing season solar radiation, average temperature, and precipitation in different wheat-growing districts in the NCP under current climate (1961–2010)

Wheat-growing districts	Model	Yield Gaps	Radiation		Temperature		Precipitation	
			Slope	R^2	Slope	R^2	Slope	R^2
I	CRUM	YG_R	3.84	0.06**	1004.4	0.33**	− 19.94	0.40**
		YG_I	3.05	0.04**	894.5	0.28**	− 19.83	0.42**
		YG_{II}	3.43	0.06**	719.7	0.23**	− 18.00	0.44**
	APSIM	YG_R	− 4.65	0.13**	− 283.7	0.004	− 25.77	0.34**
		YG_I	− 3.67	0.10**	− 496.8	0.02**	− 24.54	0.38**
		YG_{II}	− 2.05	0.04**	− 728.3	0.05**	− 20.86	0.38**
II	CRUM	YG_R	1.62	0.008	1359.7	0.45**	− 23.10	0.48**
		YG_I	1.31	0.006	1327.4	0.46**	− 21.27	0.44**
		YG_{II}	1.87	0.01	1133.9	0.40**	− 19.64	0.44**
	APSIM	YG_R	− 1.07	0.01*	− 731.7	0.03**	− 24.06	0.36**
		YG_I	− 0.48	0.003	− 562.5	0.02**	− 21.80	0.41**
		YG_{II}	0.002	9E-08	− 389.9	0.02*	− 19.36	0.46**
III	CRUM	YG_R	3.06	0.06**	698.8	0.18**	− 15.18	0.43**
		YG_I	2.71	0.05**	720.7	0.20**	− 13.20	0.35**
		YG_{II}	3.22	0.08**	449.9	0.10**	− 16.61	0.46**
	APSIM	YG_R	0.99	0.009	− 572.1	0.02**	− 23.81	0.40**
		YG_I	1.68	0.03**	− 700.8	0.03**	− 21.62	0.43**
		YG_{II}	1.87	0.06**	− 716.7	0.04**	− 17.17	0.38**
IV	CRUM	YG_R	6.70	0.12**	1320.6	0.33**	− 14.77	0.34**
		YG_I	6.31	0.13**	1087.6	0.28**	− 12.52	0.30**
		YG_{II}	5.21	0.10**	1079.3	0.30**	− 11.21	0.26**
	APSIM	YG_R	4.27	0.11**	− 873.5	0.03**	− 11.26	0.14**
		YG_I	3.43	0.11**	− 522.8	0.02*	− 10.59	0.18**
		YG_{II}	2.14	0.04**	− 167.2	0.002	− 8.41	0.12**
V	CRUM	YG_R	6.89	0.14**	943.1	0.15**	− 10.71	0.48**
		YG_I	6.79	0.16**	693.1	0.10**	− 9.42	0.44**
		YG_{II}	5.59	0.12**	865.2	0.17**	− 7.84	0.34**
	APSIM	YG_R	2.64	0.05**	− 1038	0.07**	− 7.04	0.20**
		YG_I	1.59	0.05**	− 383.7	0.02*	− 3.59	0.15**
		YG_{II}	0.57	0.04**	− 131.7	0.02*	− 1.04	0.07**

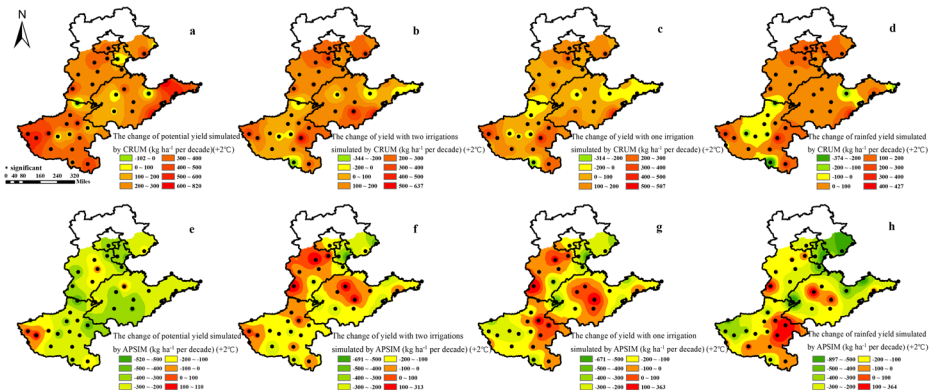**Significant at $P < 0.01$; *significant at $P < 0.05$

Fig. 5 Changes in potential, irrigated, and rainfed wheat yields in the North China Plain simulated by climatic resource utilization model (CRUM) (**a–d**) and APSIM (**e–h**) under the scenario of + 2 °C

the current climate (1961–2010). Similar to yield, consistent relationships of YG_R, YG_I, and YG_{II} simulated by CRUM and APSIM and growing season solar radiation, average temperature, and precipitation were found between the scenarios of + 2 °C and current climate because of the same climate variability (data not shown).

3.3 Trends in wheat yields and yield gaps between current and warming climates

Wheat yields simulated by CRUM increased under current climate and warming scenario of + 2 °C in different wheat-growing districts except the yields (Y_{IIW} and Y_{RW}) in district V (Fig. 7a). The highest increases of simulated yields (Y_P, Y_{II}, Y_I, Y_R, Y_{PW}, Y_{IIW}, Y_{IW}, and Y_{RW}) by CRUM were in district IV. The lowest increases of simulated yields (Y_{II} and Y_R) by CRUM were in district V, the lowest increases of simulated yields (Y_P, Y_{PW} and Y_{RW}) by CRUM were in district III, the lowest increases of simulated yields (Y_{IW} and Y_{IIW}) by CRUM were in district II, and the lowest increases of simulated yields (Y_I) by CRUM were in district I. However, wheat yields simulated by APSIM decreased under current climate and warming scenario of + 2 °C in different wheat-growing districts except Y_R in district II (Fig. 7b). The highest decreases of simulated yields (Y_R and Y_P) by APSIM were in district I. The highest decreases of simulated yields (Y_I and Y_{RW}) by APSIM were in district II. The highest decreases of simulated yield (Y_{PW}) by APSIM were in district III. The highest decreases of simulated yields (Y_{II}, Y_{IIW} and Y_{IW}) by APSIM were in district V. The lowest decreases of simulated yields (Y_P and Y_{PW}) by APSIM were in district II, the lowest decreases of simulated yields (Y_I, Y_{IIW}, Y_{IW}, and Y_R) by APSIM were in district IV, and the lowest decreases of simulated yield (Y_{RW}) by APSIM were in district V and simulated yield (Y_{II}) by APSIM were in district I.

Wheat yield gaps simulated by CRUM increased under current climate and warming scenario of + 2 °C in different wheat-growing districts (Fig. 7c). The highest increases of simulated yield gaps (YG_R, YG_I, YG_{II}, YG_{RW}, YG_{IW}, and YG_{IIW}) by CRUM were in district V. The lowest increases of simulated yield gaps (YG_R, YG_I, YG_{IW}, and YG_{II}) by CRUM were in district III, and the lowest increases of simulated yield gaps (YG_{RW} and YG_{IIW}) by CRUM were in district I. However, wheat yield gaps simulated by APSIM
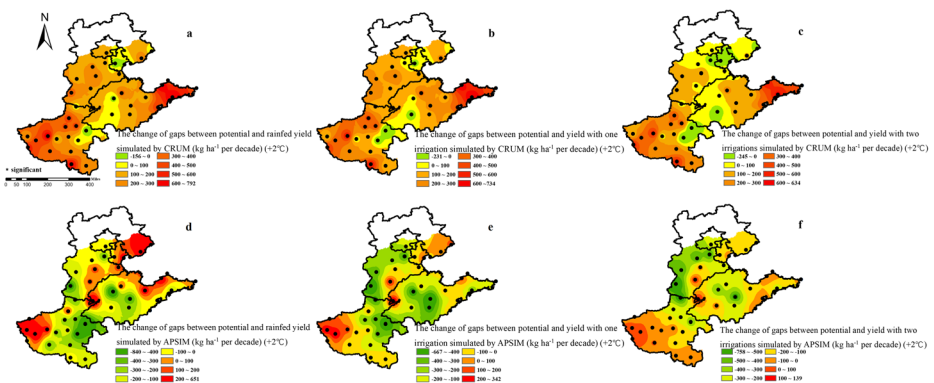

Fig. 6 Changes in the gaps between potential yield and the yields under rainfed, one irrigation, and two irrigations in the North China Plain simulated by climatic resource utilization model (CRUM) (**a**–**c**) and APSIM model (**d**–**f**) under the scenario of + 2 °C
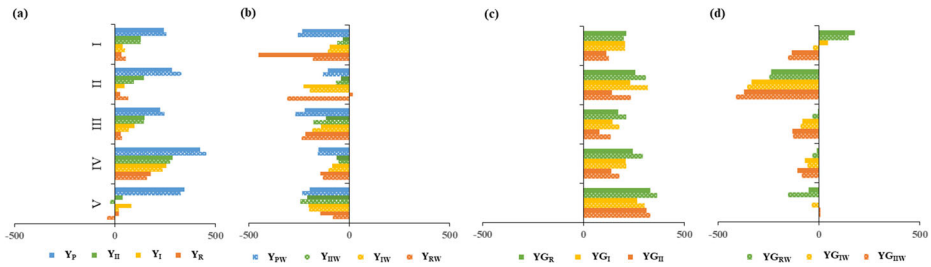
Fig. 7 Changes in wheat yields and yield gaps (kg ha^{-1} per decade) simulated by climatic resource utilization model (**a**, **c**) and APSIM (**b**, **d**) in different wheat-growing districts under current climate and warming scenario of + 2 °C

decreased under current and warming scenario of + 2 °C in different wheat-growing districts except YG$_R$, YG$_{RW}$, and YG$_I$ in district I and YG$_{II}$ and YG$_{IIW}$ in district V (Fig. 7d). The highest decreases of simulated yield gaps (YG$_R$, YG$_I$, YG$_{II}$, YG$_{RW}$, YG$_{IW}$, and YG$_{IIW}$) by APSIM were in district II. The lowest decreases of simulated yield gaps (YG$_R$) by APSIM were in district III. The lowest decreases of simulated yield gaps (YG$_{IW}$) by APSIM were in district I, and the lowest decreases of simulated yield gaps (YG$_{RW}$, YG$_I$, YG$_{II}$, and YG$_{IIW}$) by APSIM were in district IV.

4 Discussion

Although our study did not focus on simulated average potential, irrigated, and rainfed yields, the simulated wheat yields by APSIM were similar to those simulated by other crop growth models, such as EPIC (Lu and Fan 2013) and WOFOST (Wu et al. 2006). The simulated potential wheat yield by climatic resource utilization model was similar to that simulated by the agro-ecological zone (AEZ) model (Wang et al. 2010a). These results indicated that two types of models could be used to represent the potential, irrigated, and rainfed yield levels in the North China Plain. The former is a robust method in assessing climate change impacts because it could reflect crop growth and development process and interactions of genotype, environment, and management (He et al. 2017a). However, crop growth models need detailed calibration and validation based on crop and soil data. The latter was used widely to assess crop productivity at the regional scale by conducting a simple yield-climate relationship without considering complex growth and development process.

The CRUM and APSIM produced significant differences in the change rates of potential, irrigated, and rainfed yields and their yield gaps under both current climate and future warming scenarios. Similar sensitivity analysis for APSIM and CRUM was conducted in wheat planting regions in Southeast Australia and Southwest China respectively (Wang et al. 2009; He et al. 2017b), which was consistent with our results in the NCP. The key difference in response to climate change between two methods was possibly caused by different lengths of wheat-growing period in the long-term simulation. APSIM used a single variety during the long-term simulation, and therefore, past climate warming would decrease wheat yields due to shortened growing period (Wang et al. 2012). However, CRUM simulated the impact of climate change on wheat yields assuming a constant growing period implying a continuous cultivar adaptation (He et al.

2017b). Therefore, rising temperature increased wheat yields when average temperature did not exceed the optimal temperature of wheat growth. Our previous studies confirmed that continuous selection of new wheat varieties was able to compensate the negative impact of climate warming on crop growing duration (Wang et al. 2012, 2013). Thus, using a constant growing period can be justified for climate change scenario, which represents the maximum growing season for improved wheat cultivars (He et al. 2017b). Therefore, the adaptation potential by changing the length of growing period under future warming scenarios could be evaluated by combining the two types of models. The study offered a new view to evaluate the adaption potential by breeding wheat cultivar to maintain a stable growing period under different climate change scenarios and different irrigation management practices. Here, to compare the sensitivity of wheat yield and yield gap to temperature change with two contrasting models, we used a simple warming scenario with the same increase by + 2 °C in maximum and minimum temperatures. In fact, the temperature increase was asymmetric with higher increase in minimum temperature than maximum temperature (Peng et al. 2004, 2013; Lobell 2007; Fan et al. 2015). The asymmetry temperature increase would have significantly different impacts on wheat yield than symmetric increase in maximum and minimum temperatures. However, this would not influence the main conclusion of our study because the key difference in response to climate change between two methods was different lengths of wheat-growing period.

Previous studies also showed adoption of new crop cultivars could stabilize the length of pre-flowering period against the negative effect of warming and extend the length of the post-flowering (grain-filling period), which has led to the increase in wheat yield (Wang et al. 2012; Qin et al. 2013b). Moreover, Tao et al. (2014) showed that yield increased in northern China by 11.8% for each 1 °C increase in T_{mean} when wheat cultivars were shifted frequently. Other results suggested that winter wheat potential and rainfed yields would be promoted under rising temperature if crop growth period could be stabilized by cultivar adaptation. Although previous studies demonstrated that the wheat cultivar development can compensate the negative effects of climatic change (Zhou et al. 2007; Xiao et al. 2012), these studies did not separate the contribution of change in crop growth period on crop yield because the cultivar shift included the changes in several properties. In addition, field experiments showed that winter wheat could partly adapt to the warming condition by adjusting its growth (Hou et al. 2012).

Moreover, previous studies focused on the impact of climate change on wheat yield under potential and rainfed conditions. However, wheat production is neither under potential nor under rainfed condition due to limited available water resource in the NCP (Fang et al. 2010). Farmers apply one to two irrigations during the key development stage of winter wheat in the NCP. Our study considered the interaction impact of climate change and irrigation amounts on wheat yields and yield gaps and found that the adaptation potential by prolonging growth period of wheat increased with the increase in irrigation amount.

Simulating the potential and rainfed yields are helpful for understanding the limitation of light, temperature, and rainfall resources on crop productivity (Yuan et al. 2012; He et al. 2017b). In this study, we analyzed the relationships between climate factors and simulated potential and rainfed yields and yield gaps with two types of models in the NCP over the current and warming climates. Analysis on the basic climate data indicated that the change of average growing season solar radiation and average temperature in

five wheat-growing districts ranged from − 49.8 to − 19.6 MJ m^{-2} per decade and from 0.26 to 0.43 °C per decade. The change in simulated potential yield by APSIM was determined by growing season solar radiation more than growing season temperature (Tao et al. 2006; Piao et al. 2010; Chen et al. 2013). Therefore, simulated potential yield by APSIM decreased significantly due to the decline in biomass accumulation caused by shortening growth period and decreasing daily solar radiation together. However, under constant growing period, simulated potential yield by CRUM was determined by growing season temperature rather than growing season solar radiation. Therefore, the increase in temperature had a positive impact on wheat potential yield and compensated the negative impact of decreasing daily solar radiation on wheat potential yield. The results suggested that wheat yield could be maintained by effective utilization of crop growth duration by breeding new wheat cultivars under the future warming scenarios (+ 2 °C) in the NCP (Foulkes et al. 2011; Li et al. 2016b). In order to focus on the sensitivity of potential, irrigated, and rainfed yields of winter wheat to warming, the study only considered the change in the temperature. Moreover, no significant precipitation change trend was found under the current climate and future climate change scenarios (Fu et al. 2009; Hu et al. 2013; Liu et al. 2013) and the impact of change in CO_2 concentration on wheat is controversial (Reich et al. 2018). However, further studies should be conducted to investigate the impact of climate change including the change in temperature, precipitation, CO_2 concentration, and extreme weather and climate events on potential, irrigated, and rainfed yields.

5 Conclusions

Our study investigated the sensitivity of yields and yield gaps of winter wheat to climate warming in the North China Plain based on two contrasting methods. Simulated potential, irrigated, and rainfed yields of winter wheat by APSIM decreased while simulated potential, irrigated, and rainfed yields of winter wheat by CRUM would increase under rising temperature scenario by 2 °C. Under rainfed and one and two irrigations, and potential conditions under climate warming, simulated wheat yields by CRUM would increase by 13%, 28%, 23%, and 27% while simulated wheat yields by APSIM model would decrease by 17%, 10%, 8%, and 7% across the NCP in comparison with winter wheat yields under current climate. In addition, simulated yield gaps between potential yield and the yields under rainfed and one and two irrigations by CRUM increased by 33%, 27%, and 32% while simulated yield gaps between potential yield and the yields under rainfed and one and two irrigations by APSIM decreased by − 9%, 12%, and 10% respectively under the + 2 °C scenarios compared with the current climate across the NCP.

Contrasting differences in simulated wheat potential yields and yield gaps were caused mainly by different assumption on the length of wheat growth period. Without cultivar change, i.e., using APSIM model, the shortened growth period due to the increase in temperature would lead to the decrease in wheat yields and yield gaps. However, the increase in temperature with a constant growth period, i.e., using CRUM model, would increase wheat yields and yield gaps under current and warming climates. The significant differences between two contrasting methods suggested that wheat yields could be maintained and even promoted by effective utilization of crop growth duration by breeding new wheat cultivars under the future warming scenarios in the NCP.

References

Allen RG, Pereira LS, Rates D et al (1998) Crop evapotranspiration–guidelines for computing crop water requirements. FAO Irrigation and Drainage Paper 56, Rome, FAO, pp 300

Chen C, Wang E, Yu Q (2010a) Modelling the effects of climate variability and water management on crop water productivity and water balance in the North China Plain. Agric Water Manag 97:1175–1184

Chen C, Wang E, Yu Q et al (2010b) Quantifying the effects of climate trends in the past 43 years (1961–2003) on crop growth and water demand in the North China Plain. Clim Chang 100:559–578

Chen C, Baethgen WE, Robertson A (2013) Contributions of individual variation in temperature, solar radiation and precipitation to crop yield in the North China Plain, 1961-2003. Clim Chang 116:767–788

Cong Z, Wang S, Ni G (2008) Simulations of the impact of climate change on winter wheat production. J Tsinghua Univ (Sci Tech) 48:1426–1430 (in Chinese)

Diepen CA, Wolf J, Keulen H et al (1989) WOFOST: a simulation model of crop production. J Soil Use Manag 5:16–24

Ding Y, Ren G, Shi G et al (2006) National assessment report of climate change (I): climate change in China and its future trend. Adv Clim Chang Res 2:3–8 (in Chinese)

Fan Y, Tian M, Jing Q et al (2015) Winter night warming improves pre-anthesis crop growth and post-anthesis photosynthesis involved in grain yield of winter wheat (*Triticum aestivum* L.). Field Crop Res 178:100–108

Fang Q, Ma L, Green TR et al (2010) Water resources and water use efficiency in the North China Plain: current status and agronomic management options. Agric Water Manag 97:1102–1116

FAO (2013) FAO statistical databases. FAO, Rome

Foulkes M, Slafer GA, Davies WJ et al (2011) Raising yield potential of wheat. III. Optimizing partitioning to grain while maintaining lodging resistance. J Exp Bot 62:469–486

Fu G, Charles SP, Yu J et al (2009) Decadal climatic variability, trends and future scenarios for the North China Plain. J Clim 22:2111–2123

He D, Wang J, Dai T et al (2014) Impact of climate change on maize potential productivity and the potential productivity gap in Southwest China. J Meteorol Res 28:1155–1167

He D, Wang E, Wang J et al (2017a) Genotype × environment × management interactions of canola across China: a simulation study. Agric For Meteorol 247:424–433

He D, Wang J, Pan Z et al (2017b) Changes in wheat potential productivity and drought severity in Southwest China. Theor Appl Climatol 130:477–486

Hou R, Zhu O, Li Y et al (2012) Is the change of winter wheat yield under warming caused by shortened reproductive period? Ecol Evol 2:2999–3008

Hu X, Wang J, Feng L (2013) Analysis on agro-climatic elements variation during winter wheat growing season in North China Plain. Chin J Agrometeorol 34:317–323 (in Chinese)

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

Jones CA, Kiniry JR (1986) CERES-maize: a simulation model of maize growth and development. Texas A & M University Press, College Station, p 194

Keating BA, Carberry PS, Hammer GL et al (2003) An overview of APSIM, a model designed for farming systems simulation. Eur J Agron 18:267–288

King AD, Donat MG, Lewis SC et al (2018) Reduced heat exposure by limiting global warming to 1.5 °C. Nat Clim Chang 8:549–551

Li K, Yang X, Liu Y et al (2012) Distribution characteristics of winter wheat yield and its influenced factors in North China. Acta Agron Sin 38:1483–1493 (in Chinese)

Li K, Yang X, Liu Z et al (2014) Low yield gap of winter wheat in the North China Plain. Eur J Agron 59:1–12

Li J, Wang E, Wang Y et al (2016a) Reducing greenhouse gas emissions from a wheat–maize rotation system while still maintaining productivity. Agric Syst 145:90–98

Li K, Yang X, Tian H et al (2016b) Effects of changing climate and cultivar on the phenology and yield of winter wheat in the North China Plain. Int J Biometeorol 60:21–32

Liu B, Xu M, Henderson M et al (2005) Observed trends of precipitation amount, frequency, and intensity in China, 1960-2000. J Geophys Res 110:D08103

Liu W, Fu G, Liu C et al (2013) Projection of future rainfall for the North China Plain using two statistical downscaling models and its hydrological implications. Stoch Environ Res Risk Assess 27:1783–1797

Lobell DB (2007) Changes in diurnal temperature range and national cereal yields. Agric For Meteorol 145:229–238

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

Peng S, Huang J, Sheehy JE et al (2004) Rice yields decline with higher night temperature from global warming. PNAS 101:9971–9975

Peng S, Piao S, Ciais P et al (2013) Asymmetric effects of daytime and night-time warming on northern hemisphere vegetation. Nature 501:88–92

Piao S, Ciais P, Huang Y et al (2010) The impacts of climate change on water resources and agriculture in China. Nature 467:43–51

Porter JR, Gawith M (1999) Temperatures and the growth and development of wheat: a review. Eur J Agron 10:23–36

Porter JR, Xie L, Challinor A et al (2014) Food security and food production systems. Climate Change 2014 Impacts, adaptation, and vulnerability. Contribution of Working Group II to Fifth Assessment Report of the Intergovernmental Panel Climate Change

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

Qin Y, Liu J, Shi W et al (2013b) Spatial-temporal changes of cropland and climate potential productivity in northern China during 1990-2010. Food Sec 5:499–512

Reich PB, Hobbie SE, Lee TD et al (2018) Unexpected reversal of C-3 versus C-4 grass response to elevated CO_2 during a 20-year field experiment. Science 360:317–320

Sun H, Zhang X, Chen S et al (2007) Effects of harvest and sowing time on the performance of the rotation of winter wheat-summer maize in the North China Plain. Ind Crop Prod 25:239–247

Tang J, Wang J, He D et al (2016) Comparison of the impacts of climate change on potential productivity of different staple crops in the agro-pastoral ecotone of North China. J Meteorol Res 30:983–997

Tao F, Yokozawa M, Xu Y et al (2006) Climate changes and trends in phenology and yields of field crops in China, 1981-2000. Agric For Meteorol 138:82–92

Tao F, Zhang Z, Xiao D et al (2014) Responses of wheat growth and yield to climate change in different climate zones of China, 1981-2009. Agric For Meteorol 189:91–104

Wang E, Yu Q, Wu D et al (2008) Climate, agricultural production and hydrological balance in the North China Plain. Int J Climatol 28:1959–1970

Wang J, Wang E, Luo Q et al (2009) Modelling the sensitivity of wheat growth and water balance to climate change in Southeast Australia. Clim Chang 96:79–96

Wang H, Chen F, Shi Q et al (2010a) Analysis of factors on impacting potential productivity of winter wheat in Huanghuaihai agricultural area over 30 years. Trans Chin Soc Agric Eng 26:90–95 (in Chinese)

Wang J, Zhao T, Wang E et al (2010b) Measurement and simulation of diurnal variations in water use efficiency and radiation use efficiency in an irrigated wheat-maize field in the North China Plain. NZJC&HS 38:119–135

Wang J, Wang E, Yang X et al (2012) Increased yield potential of wheat-maize cropping system in the North China Plain by climate change adaptation. Clim Chang 113:825–840

Wang J, Wang E, Feng L et al (2013) Phenological trends of winter wheat in response to varietal and temperature changes in the North China Plain. Field Crop Res 144:135–144

Wang J, Wang E, Yin H et al (2015) Differences between observed and calculated solar radiations and their impact on simulated crop yields. Field Crop Res 176:1–10

Wang N, Wang E, Wang J et al (2018) Modelling maize phenology, biomass growth and yield under contrasting temperature conditions. Agric For Meteorol 250:319–329

Wu D, Yu Q, Lu C et al (2006) Quantifying production potentials of winter wheat in the North China Plain. Eur J Agron 24:226–235

Xiao Y, Qian Z, Wu K et al (2012) Genetic gains in grain yield and physiological traits of winter wheat in Shandong province, China, from 1969 to 2006. Crop Sci 52:44–56

Xu F, Zhao B (2001) Development of crop yield and water use efficiency in Fengqiu county, China. Acta Pedol Sin 38:491–497 (in Chinese)

Yuan B, Guo J, Ye M et al (2012) Variety distribution pattern and climatic potential productivity of spring maize in Northeast China under climate change. Chin Sci Bull 57:3497–3508 (in Chinese)

Zhang X, Chen S, Liu M et al (2005) Improved water use efficiency associated with cultivars and agronomic management in the North China Plain. Agron J 97:783–790

Zhang J, Zhao Y, Wang C et al (2006) Effects of climate change on winter wheat growth and yield in North China. Chin J Appl Ecol 17:1179–1184 (in Chinese)

Zhang Y, Feng L, Wang E et al (2012) Evaluation of the APSIM-Wheat model in terms of different cultivars, management regimes and environmental conditions. Can J Plant Sci 92:937–946

Zhao J, Guo J, Wu D et al (2011) Climatic potential productivity of winter wheat and summer maize in Huanghuaihai Plain in 2011-2050. Chin J Appl Ecol 22:3189–3195 (in Chinese)

Zhou Y, He Z, Sui X et al (2007) Genetic improvement of grain yield and associated traits in the northern China winter wheat region from 1960 to 2000. Crop Sci 47:245–253

Publisher's note   Springer Nature remains neutral with regard to jurisdictional claims in published maps and institutional affiliations.