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RESEARCH ARTICLE

Comparison of winter wheat yield sensitivity to climate variables under irrigated and rain-fed conditions

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Abstract Crop simulation models provide alternative, less time-consuming, and cost-effective means of determining the sensitivity of crop yield to climate change. In this study, two dynamic mechanistic models, CERES (Crop Environment Resource Synthesis) and APSIM (Agricultural Production Systems Simulator), were used to simulate the yield of wheat (*Triticum aestivum* L.) under well irrigated (CFG) and rain-fed (YY) conditions in relation to different climate variables in the North China Plain (NCP). The study tested winter wheat yield sensitivity to different levels of temperature, radiation, precipitation, and atmospheric carbon dioxide (CO_2) concentration under CFG and YY conditions at Luancheng Agro-ecosystem Experimental Stations in the NCP. The results from the CERES and APSIM wheat crop models were largely consistent and suggested that changes in climate variables influenced wheat grain yield in the NCP. There was also significant variation in the sensitivity of winter wheat yield to climate variables under different water (CFG and YY) conditions. While a temperature increase of 2°C was the threshold beyond which temperature negatively influenced wheat yield under CFG, a temperature rise exceeding 1°C decreased winter wheat grain yield under YY. A decrease in solar radiation decreased wheat grain yield under both CFG and YY conditions. Although the sensitivity of winter wheat yield to precipitation was small under the CFG, yield decreased significantly with decreasing precipitation under the rain-fed YY treatment. The results also suggest that wheat yield under CFG linearly increased by $\approx 3.5\%$ per 60 ppm (parts per million) increase in CO_2 concentration from 380 to 560 ppm, and yield under YY increased linearly by $\approx 7.0\%$ for the same increase in CO_2 concentration.

Keywords winter wheat, yield sensitivity, climate variables, crop model, North China Plain

1 Introduction

As a main indicator for global change, ongoing climate warming has had significant impact on human life, including agricultural production for human consumption (IPCC, 2013). Crop phenology and yield response to climate change have been critical in the study of the impacts of climate change on agricultural production (Porter and Gawith, 1999; Lobell et al., 2011; Xiao et al, 2013a, 2015). Hence, the potential impacts of climate change on crop production have been extensively studied over the past several decades (Tao et al., 2003; Luo et al., 2010; Xiao and Tao, 2014). Sensitivity analysis, as a common method of quantifying the potential impacts of climate change on crop production (Southworth et al., 2002; Wang et al., 2009; Luo and Kathuria, 2013), has been applied to many agricultural impact studies (Brown and Rosenberg, 1997; Olesen et al., 2000; van Ittersum et al., 2003; Goldblum, 2009). Simulation designs for sensitivity analysis have evolved from a single level of a single factor to multiple levels of multiple factors via permutations of temperature, radiation, precipitation, and atmospheric carbon dioxide (CO_2) concentration (Luo and Kathuria, 2013).

Crop simulation models consider the complex interactions between weather, soil properties, and management that influence crop performance (Jones et al., 2003; Keating et al., 2003). Thus, crop models should be able

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to reproduce experimental results for a range of environmental conditions (Wilcox and Makowski, 2014). In addition, results of crop model simulations are often used to inform policy makers about the effects of climate change on crop productivity (Challinor et al., 2009). There is now a large availability of crop models for various environmental and research conditions, making it possible to focus on specific aspects of the plant-soil-climate system (Porter et al., 1993; Hammer et al., 2010; Tian et al., 2012; Zhang et al., 2014). Because these models could vary in the description of crop processes, input requirements, and sensitivity to environmental conditions (Palosuo et al., 2011), there is a need to compare different modeling approaches to determine uncertainties in model-simulated crop growth and yield (Jamieson et al., 1998; Eitzinger et al., 2004; Martre et al., 2014).

Wheat (*Triticum aestivum* L.) is moderately resistant to frost and drought, and is grown under a temperature range of -40°C to $+40$°C. Winter wheat is planted in the fall, germinates, and survives snow cover and a low temperature of -30°C. The wheat seedlings rapidly grow in the following spring and mature before summer heat (Wittwer, 1995). As the third main food crop after rice (*Oryza*) and maize (*Zea*), wheat is a traditionally a high-end crop in China (Xiao et al., 2013b). Suitable climatic conditions and fertile soils in the North China Plain (NCP) favor extensive winter wheat production (Sun et al., 2006; Chen et al., 2010; Xiao et al., 2013a). Several studies have noted that the trends in climate affect the phenology and productivity of wheat in the NCP (Xiao et al., 2013a; Shi and Tao, 2014; Tao et al., 2014; Xiao and Tao, 2014; Zhang et al., 2015). Although several studies have also reported different sensitivities of winter wheat yield to climate variables (i.e., temperature, solar radiation, precipitation, and CO_2) (Zhang et al., 2004; Xiao and Tao, 2014), less work has been done on the response and sensitivity of winter wheat yield to climate variables under different soil water (irrigated and rain-fed) conditions in the NCP.

In this study, the performances of two dynamically mechanistic crop growth models — CERES (Crop Environment Resource Synthesis) and APSIM (Agricultural Production Systems Simulator) — were calibrated, validated, and compared in terms of yield sensitivity to climate variables under different soil water conditions at the Luancheng Agro-ecosystem Experimental Station (LAS) in the NCP. The objectives of the study were: (i) to use phenological and yield data to calibrate and validate CERES-Wheat and APSIM-Wheat under irrigated (CFG) and rain-fed (YY) conditions; and (ii) to compare the sensitivity of winter wheat yield to a range of climate variables under CFG and YY between CERES-Wheat and APSIM-Wheat models.

2 Methodology

2.1 Field experiments

Field experiments were conducted at Luancheng Agro-ecosystem Experimental Station (37°53′N, 114°41′E, 50.1 m), located in the high-yield zone of the NCP (Sun et al., 2006). Table 1 lists the characteristics and parameters of the loamy topsoil in the study area, which is highly fertile and rich in organic matter. The climate is a temperate semi-arid monsoon type with a mean annual temperature of 12.2°C, radiation of 524 kJ/cm^2, and precipitation of 481 mm (Sun et al., 2006; Iqbal et al., 2014). About 75% of the precipitation occurs in the summer months of late June through September. In the study area, winter wheat is grown from early October to mid-June. The rainfall is not sufficient for normal growth wheat, especially during the dry, windy spring season. Therefore crop high yield output in the region is mainly supported by intensive irrigation (Xiao and Tao, 2014).

Experiments on winter wheat were conducted in seven consecutive seasons from 2006 through 2013. Table 2 shows the sowing date and weather conditions during the winter wheat growth seasons in 2006–2013 at LAS. A total of 16 plots (each with dimension of 5 m × 10 m) were set up in 1995, separated by concrete walls 24.5 cm thick and buried 1.5 m deep as specified by the Food and Agricultural Organization (FAO) (Zhang et al., 2004).

“Kenong 199” winter wheat was sown in early October at a seed rate of 150 kg·ha^{-1} with 20 cm row width and then harvested in mid June in the following year. Before

Table 1 Soil properties at the experimental site of Luancheng Agro-experimental Station in North China Plain

Soil depth	Texture	BD/(g·cm^{-3})	SAT/(mm·mm^{-1})	DUL/(mm·mm^{-1})	LL/(mm·mm^{-1})
0–20	Sandy loam	1.41	0.44	0.36	0.10
20–40	Sandy loam	1.51	0.46	0.35	0.11
40–60	Light loam	1.47	0.43	0.33	0.14
60–100	Medium loam	1.51	0.43	0.34	0.14
100–140	Light clay	1.54	0.44	0.34	0.13
140–170	Light clay	1.64	0.44	0.39	0.14
170–200	Light clay	1.59	0.48	0.38	0.16

Note that BD denotes bulky density, SAT is saturation, DUL is field capacity and LL is lower limit.

Table 2 Sowing date and weather conditions during winter wheat growth seasons in 2006–2013 at Luancheng Agro-experimental Station in North China Plain

Year	Sowing date	Maximum temperature/°C	Minimum temperature/°C	Radiation/($MJ \cdot m^{-2}$)	Precipitation/mm
2006–2007	10 October	15.3	5.0	12.2	160.3
2007–2008	14 October	14.2	4.2	12.3	183.1
2008–2009	7 October	15.6	4.5	12.9	94.4
2009–2010	11 October	12.3	2.9	12.3	116.1
2010–2011	11 October	14.3	3.7	13.4	68.3
2011–2012	7 October	13.8	4.6	11.8	107.5
2012–2013	12 October	12.6	3.6	11.9	153.4

Table 3 Irrigation treatments used in the 2006–2013 experimental winter wheat period at Luancheng Agro-experimental Station in North China Plain

Treatment	Growth stage and irrigation treatment (θ/θ_{FC})			
	Sowing	Spring greening	Stem extension	Grain filling
CFG	1.0	1.0	1.0	1.0
FQX	0.8	0	0.8	0.8
BJX	0.8	0.8	0	0.8
GJX	0.8	0.8	0.8	0
YY	0	0	0	0

CFG denotes four times of irrigation, FQX is no irrigation at spring greening stage, BJX is no irrigation at stem extension stage, GJX is no irrigation at grain filling stage and YY is rain fed; θ is average soil water content of crop root depth (0 – 1.2 m); θ_{FC} is average field capacity of crop root depth. 1.0 or 0.8 means the ratio of θ to θ_{FC}.

sowing, the soil was manually treated with nitrogen (N) and phosphorus (P) fertilizers at 130 $kg \cdot ha^{-1}$ N and 160 $kg \cdot ha^{-1}$ P_2O_5. To eliminate the effect of plot mulching, straws of previous crops (mainly maize) were removed. Winter wheat yield was sampled from a portion in the central area of each plot. A total of five irrigation treatments were adopted (Table 3). With the exception of treatment YY (which had four replications), each treatment was replicated three times.

2.2 Model description

As CERES-Wheat and APSIM-Wheat are the most commonly used crop simulation models around the world, the two models have been extensively evaluated against a range of agricultural, climatic, and environmental conditions across the world in terms of the use of the models to simulate crop yield.

2.2.1 CERES-Wheat

CERES-Wheat is embedded in DSSAT (Decision Support System for Agro-technology Transfer) version 4.0.2 crop systems model (Jones et al., 2003). The model describes the processes that occur in the life-cycle of a given crop on the basis of cumulative degree-day. CERES-Wheat model simulates crop growth, development, and yield, taking into account the effects of weather, genetic, soil, and management conditions. The duration of the growth stage in response to temperature and photoperiod varies with crop species and cultivars, which is put into the model as a genetic coefficient.

The model predicts daily photosynthesis using the Radiation Use Efficiency (RUE) approach. RUE is a function of daily irradiance for a full canopy, which is multiplied by factor of 0 to 1 for light interception, temperature, leaf N status, and water deficit. Growth of new tissues depends on daily available carbohydrate and partitioning to different tissues as a function of phenological stage and as modified by water deficit and N deficiency stress.

Genetic coefficients are used to describe various crop species and cultivar types. CERES-Wheat uses seven genetic coefficients that are related to photoperiod sensitivity, grain-filling duration, mass-to-grain number conversion, grain-filling rate, vernalization requirements, stem size, and cold hardiness (Ritchie et al., 1998); all of which are shown in Table 4. Input requirements for CERES-Wheat include weather and soil conditions, plant characteristics, and crop management (Hunt et al., 2001). The minimum weather input requirement of CERES-Wheat includes daily solar radiation, maximum and minimum air temperature, and precipitation. Solar radiation can be approximated from more readily available observations such as sunshine hours.

Table 4 Values of parameter of the winter wheat used in CERES-Wheat model simulation in the North China Plain study area

Cultivar parameter	Parameter value
P5 [grain-filling (excluding lag) phase duration (°C·d)]	660
G1 [kernel number per unit canopy weight at anthesis (g^{-1})]	23.0
G2 [Standard kernel size under optimum conditions (mg)]	45.0
G3 [Standard, non-stressed mature tiller weight (incl grain) (g·dwt)]	2.0
PHINT [Interval between successive leaf tip appearances (°C·d)]	85
P1V [Optimum temperature required for vernalization (°C)]	20
P1D [Photoperiod response (% rate reduction /10h drop in pp)]	90

2.2.2 APSIM-Wheat

APSIM is a cropping systems simulation model developed by the Agricultural Production Systems Research Unit of Australia. APSIM is a component-driven model that runs several modules including crop growth/development and soil water/nitrogen dynamics (Keating et al., 2003). APSIM integrates predicted economic factors such as grain, biomass, and sugar yield based on changes in climate and management conditions. It predicts the long-term impacts of cropping systems on soil physio-chemical conditions (Hammer et al., 2010). The model also simulates phenological processes, biomass accumulation and partitioning, leaf area index (LAI), as well as root, stem, leaf, and grain growth in daily time step.

In its genetic crop module, APSIM uses genetic coefficients for crop growth phase duration, photoperiod sensitivity, vernalization needs, grain size, and grain-filling rate (Table 5). A detailed description of the APSIM model and its crop/soil modules is given by Keating et al. (2003). As with CERES-Wheat, the minimum weather input requirement for APSIM-Wheat includes daily maximum and minimum air temperature, solar radiation, and precipitation.

Table 5 Values of parameter of winter wheat used in APSIM-Wheat model simulation in the North China Plain study area

Cultivar parameter	Parameter value
Startgf_to_mat [Thermal time from beginning of grain-filling to maturity (°C·d)]	660
Potential_grain_filling_rate [Potential grain-filling rate (g per kernel per day)]	0.0024
Grains_per_gram_stem [Coefficient of kernel number per stem weight at the beginning of grain-filling (g per stem)]	23.0
Max_grain_size [Potential maximum grain size (g per kernel)]	0.045
Phyllochron [Phellochron interval (°C·d/leaf appearance)]	85
Vern_sens [Sensitivity to vernalization]	1.7
Photop_sens [Sensitivity to photoperiod]	2.3

2.3 Model calibration and validation

There is a need to estimate cultivar characteristics of crop models if it has not been previously done. Thus the CERES-Wheat and APSIM-Wheat used in this study were calibrated using field data collected in 2006–2009, including CFG irrigation treatment (Table 3), and phenological (anthesis and maturity date) and yield data. The calibrated crop parameters were used to run the validation analysis. Then an independent set of data was used to test the model performance for 2009–2013. Tables 4 and 5 list the crop variety parameters of CERES-Wheat and APSIM-Wheat used to simulate phenological developments and yields in LAS. The parameters were derived by matching simulated and observed phenology and yield of wheat in a trial-and-error analysis (Xiong et al., 2008).

2.4 Yield sensitivity to climate variables

Historical daily weather data, including maximum and minimum temperature, sunshine duration, and precipitation for 1971 – 2013 in LAS are from the Chinese Meteorological Administration (CMA). Solar radiation trends for the station are estimated from observed sunshine hour data using the Angstrom-Prescott equation (Prescott, 1940). To determine the sensitivity of wheat yield to climate variables (e.g., temperature, solar radiation, precipitation, and CO_2), the crop models were first control-run on each observed date for 1971–2013 with 380 ppm CO_2 concentration.

Next, the wheat crop models were run under CFG and YY conditions, holding other variables at control input values (i.e., observed weather data) but with 1°C variations in temperature (both maximum and minimum temperature) from + 1°C to + 3°C (Luo and Kathuria, 2013). Similarly, the models were run at 10% variations in radiation from – 10% to – 30%. Then precipitation was varied at 10% intervals from – 10% to – 30%, and CO_2 concentrations were varied at 60 ppm from 440 ppm to 560 ppm (van Ittersum et al., 2003).

Then the results of the CERES-Wheat and APSIM-Wheat model runs under both CFG and YY conditions for the varied climate variables (e.g., temperature, solar radiation, precipitation, and CO_2) were compared with that of the control run, and the sensitivity of wheat yield to each climate variable was finally determined.

3 Results and discussion

3.1 Simulated and field data comparison

CERES-Wheat and APSIM-Wheat models were calibrated and validated for “Kenong 199” wheat cultivar using field data from LAS for 2007–2013. The models require cultivar-specific genetic parameters that are based on real field data (see Tables 4 and 5).

As given in Table 6, the model-simulated and field-observed dates of anthesis and maturity agreed well for the period 2007–2013. The difference between the simulated and observed dates of anthesis and maturity is less than 5 days, suggesting that both CERES-Wheat and APSIM-Wheat models fairly accurately simulate winter wheat phenological stages in the study area. The two crop models were also evaluated against wheat yield under two irrigation treatments (CFG — four times of irrigation and YY — rain-fed condition), and the model-simulated versus field-measured yields were plotted in Fig. 1. Both the line of best-fit and the coefficients of determination (R^2) suggested a high degree of reliability (R^2= 0.66 – 0.91) of the simulated grain yields by the two crop models. However, the APSIM-Wheat model slightly overestimated wheat yield for the most of years under rain-fed condition (Fig. 1(b)).

The two crop models were further run under five irrigation treatments (Table 3) as field management options. As depicted in Fig. 2, the simulated average yield by the crop models was in close agreement with measured yield. However, simulated yield by the CERES-Wheat and APSIM-Wheat models under GJX (no irrigation at the grain-filling stage) and YY (rain-fed condition) was lower than the field observed value (Fig. 2).

Several different crop models (including CERES, APSIM, EPIC, WOFOST, SVAT, AquaCrop, etc.) have been evaluated and applied in the NCP (Mo et al., 2009; Chen et al., 2010; Lu and Fan, 2013; Wu et al., 2014). For example, Wu et al. (2014) used CERES to investigate

Table 6 Field-observed versus model-simulated phenology for validated analysis of winter wheat at Luancheng Agro-experimental Station in North China Plain

Phenology date	Item	2006–2007	2007–2008	2008–2009	2009–2010	2010–2011	2011–2012	2012–2013
Anthesis date	Field observation (DOY)	128	127	124	124	131	126	129
	CERE-Wheat Simulation (DOY)	127	128	127	125	130	126	128
	Deviation (day)	–1	1	3	1	1	0	–1
	APSIM-Wheat Simulation (DOY)	126	128	121	126	131	127	132
	Deviation (day)	–2	1	–3	2	0	1	3
Maturity date	Field observation (DOY)	163	164	161	160	164	161	163
	CERE-Wheat Simulation (DOY)	161	165	162	158	164	160	162
	Deviation (day)	–2	1	1	–2	0	–1	–1
	APSIM-Wheat Simulation (DOY)	162	164	156	159	166	160	165
	Deviation (day)	–1	0	–5	–1	2	–1	2

Note that DOY is day of year.

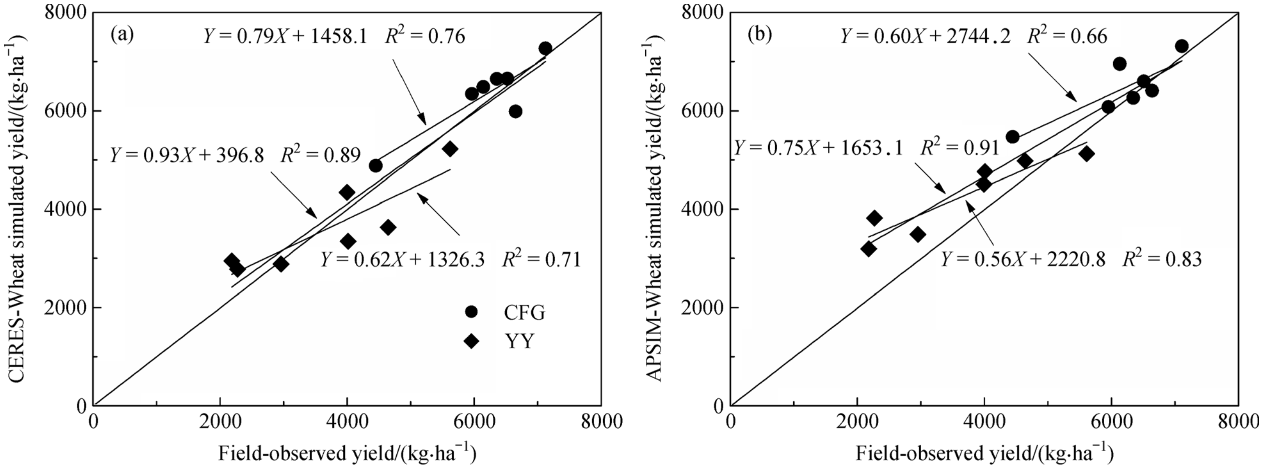

Fig. 1 Plots of CERES-Wheat (a) and APSIM-Wheat (b) model-simulated winter wheat yield against field-observed yield for validation analysis under well-irrigated (CFG) and rain-fed (YY) conditions at Luancheng Agro-experimental Station in the North China Plain.

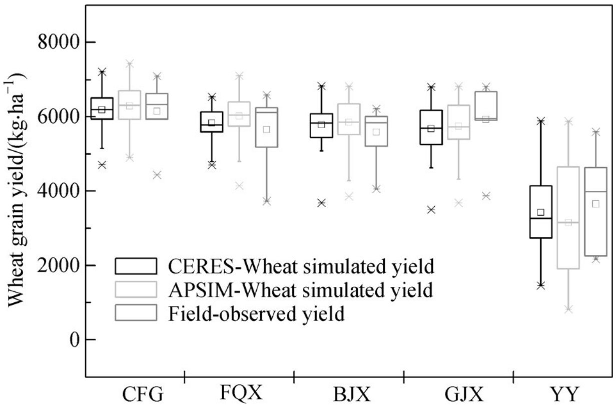

Fig. 2 Comparison of CERES-Wheat and APSIM-Wheat model-simulated yield with field-observed yield under five irrigation treatments at Luancheng Agro-experimental Station in the North China Plain. The upper and lower hinges of the box plots denote the 75th and 25th percentiles of the respective datasets. The in-box lines denote the median values and the open squares the mean values of the respective data sets. Also note that CFG, FQX, BJX, GJX and YY respectively denote four times of irrigation, no irrigation at spring greening stage, no irrigation at stem extension stage, no irrigation at grain filling stage, and rain fed.

water deficit variation during the winter wheat growing season, and its impact on crop yield. Chen et al. (2010) used APSIM to quantify the effects of climate change in 1961–2003 on crop (wheat and maize) growth and water demand. Iqbal et al. (2014) calibrated and validated the FAO AquaCrop model for deficit irrigation in the LAS and found the model highly suitable for evaluating deficit irrigation strategies. This study suggested that the CERES-Wheat and APSIM-Wheat models had a high degree of accuracy and were therefore very suitable for application in evaluating irrigation options for sustainable food security under changing climatic conditions in this study area.

3.2 Wheat yield and climate variables

A notable climate change has been observed in the NCP in the last four decades (Chen et al., 2010; Shi et al., 2014). Although a warming trend was observed for the winter wheat growth season at the LAS in this study, only the increase in minimum temperate ($0.1°\mathrm{C}\cdot\mathrm{yr}^{-1}$) was statically significant at $p < 0.01$ (Fig. 3(a) and 3(b)), especially since the 1980s. The magnitude of increase in minimum temperature was greater than that in maximum temperature. While solar radiation decreased significantly (by $0.04\ \mathrm{MJ}\cdot\mathrm{m}^{-2}\cdot\mathrm{yr}^{-1}$) during the winter wheat growth season (Fig. 3(c)), no significant change was noted in precipitation (Fig. 3(d)).

Positive (negative) correlation suggests that change in a given climate variable increases (decreases) yield (Tao et al., 2014). Significantly different degrees of correlation were noted between yield and climate variables under CFG and YY water treatments (Table 7). Under the well-irrigated CFG condition (with four times of irrigation), simulated wheat yield by the two crop models was positively correlated with maximum temperature ($T_{\max}$) and solar radiation (Rad). However, the model-simulated yield was not significantly correlated with minimum temperature ($T_{\min}$) and precipitation (Prec) (Table 7). Only under the rain-fed YY condition (with no irrigation), was simulated yield by CERES-Wheat and APSIM-Wheat significantly positively correlated with precipitation (Table 7). The two-model analysis suggested that changes in climate variables led to changes in wheat yield in the NCP study area under different water conditions. Winter wheat yield responded differently to different climate variables.

3.3 Yield sensitivity to climate variables

As shown in Figs. 4(a) and 4(b), the simulated sensitivity of winter wheat yield to mean temperature by the two crop models was more or less consistent under the two different irrigation conditions (CFG and YY). Under CFG treatment, wheat yield slightly increased by 2.4% (average for the two crop model simulations) for a 1°C temperature rise but decreased for a 2°C–3°C temperature rise (Table 8). Under YY treatment, a 1°C rise in temperature slightly decreased wheat yield on average by 1.8% while a 3°C rise in temperature decreased yield by 9.4% (Table 8). This suggested that winter wheat yield sensitivity to temperature varied with varying water conditions (irrigated or rain-fed condition). A temperature increase of 2°C under the well-irrigated condition was the threshold beyond which temperature negatively influenced wheat yield. An increase in temperature beyond the threshold value increased the degree of wheat grain loss. This study, however, showed that under rain-fed conditions, a temperature rise exceeding 1°C decreased winter wheat grain yield. The results of this study are consistent with other studies (McKeon et al., 1988; Aggarwal and Sinha, 1993; Luo and Kathuria, 2013). Aggarwal and Sinha (1993) noted that a 1°C rise in mean temperature had no significant effect on potential wheat grain yield while a 2°C rise reduced potential yield in northern India. McKeon et al. (1988) also found that a temperature increase of 2°C would decrease wheat yields by 6% in Queensland, Australia. Luo and Kathuria (2013) found that the rate of decrease in median grain yield was more for higher temperatures in contrast to lower temperatures.

Generally, lack of solar radiation during the most critical period of solar energy requirement would prevent photosynthesis and further reduce crop yields (Stansel, 1975). The sensitivity of winter wheat yield to solar radiation is plotted in Figs. 4(c) and 4(d). As in other studies (e.g., Chen et al., 2010; Tao et al., 2014; Xiao and Tao, 2014), this study noted that a decrease in solar radiation decreased wheat grain yield under both CFG and YY conditions.

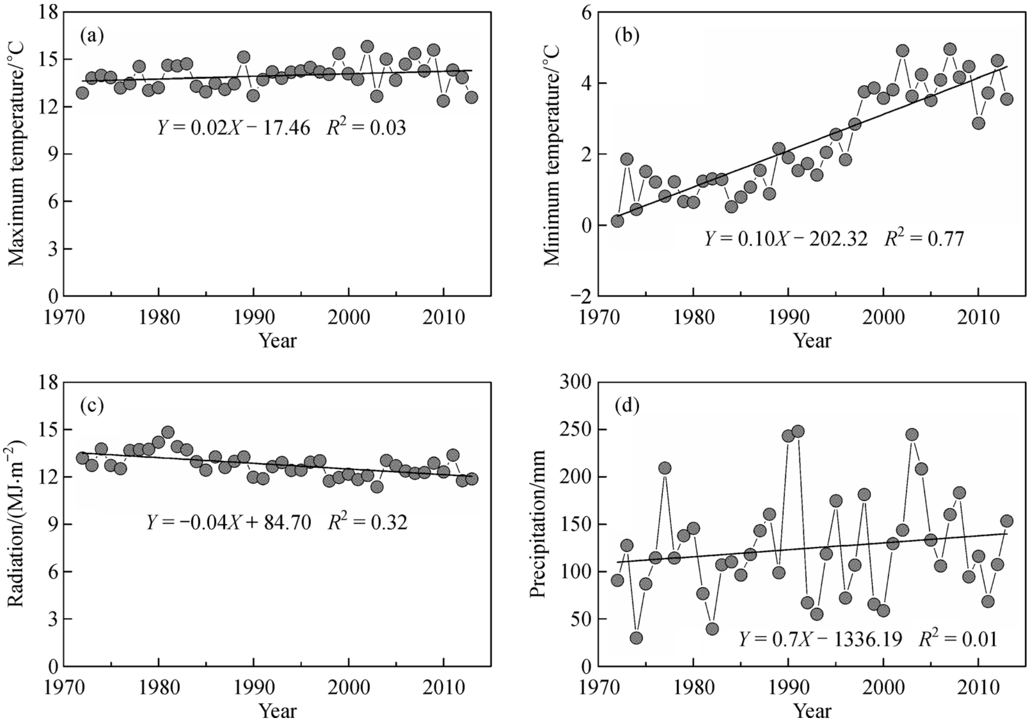

Fig. 3 Time series plots of maximum temperature (a), minimum temperature (b), solar radiation (c) and precipitation (d) during winter wheat growth seasons in 1971–2013 at Luancheng Agro-experimental Station in the North China Plain.

Table 7 Correlations between model-simulated yield and tested climate variables in the North China Plain study area

Crop model	Treatment	$T_{\max}$	$T_{\min}$	Rad	Prec
CERES-Wheat	CFG	0.48**	0.11	0.36**	−0.12
	YY	0.03	0.20	−0.14	0.61**
APSIM-Wheat	CFG	0.36*	0.13	0.40**	−0.10
	YY	0.17	0.17	−0.10	0.41**

Note that a single asterisk (*) is a significant trend at 5% probability level; a double asterisk (**) is a significant trend at 1% probability level; CFG denotes four times of irrigation, and YY is rain fed; $T_{\max}$ is maximum temperature, $T_{\min}$ is minimum temperature, Rad is solar radiation, and Prec is precipitation.

Furthermore, the model-simulated yield was more sensitive to changes in radiation under well-irrigated (CFG) condition than under rain-fed (YY) condition. For a 30% decrease in solar radiation, wheat grain yield decreased by 32.5% under CFG treatment and by only 16.9% under YY treatment (Table 8). This suggested that global dimming reduces the total amount of photo-synthetically active radiation (PAR), which in turn reduces wheat yield potential (Tao et al., 2014; Xiao and Tao, 2014). In the same study region, Zhang et al. (2013) indicated wheat yield was positively correlated with sunshine hours (solar radiation) based on the field measured data.

Due to good soil moisture conditions, the sensitivity of winter wheat yield to precipitation was small under the well-irrigated CFG condition (Fig. 4(e)). Also, wheat is prone to water-logging, insects/pests, and diseases during rainy season, which are some of the factors for the generally low yield under high precipitation conditions (Tao et al., 2014). On the contrary, simulated winter wheat yield decreased significantly with decreasing precipitation under the rain-fed YY treatment (Fig. 4(f)). As given in Table 8, wheat grain yields decreased by −19.5%, −33.6%, and −53.1% respectively for 10%, 20%, and 30% decreases in precipitation.

Due to increased photosynthesis and water use efficiency, an increase in CO_2 concentration increased wheat grain yield. Furthermore, wheat yield was more responsive to increased CO_2 concentration under drier conditions (rain-fed treatment) (Fig. 4(g) and 4(h)). Different types of plants (usually C_3 and C_4 plants based on the dominant photosynthetic pathway) respond differently to CO_2 fertilization. C_3 plants (e.g., wheat) benefit more than C_4 plants from increased atmospheric CO_2 concentration. Wheat is one of the most responsive cereal crops to CO_2 fertilization due to enhanced photosynthesis and water use efficiency (van Ittersum et al., 2003). van Ittersum et al.

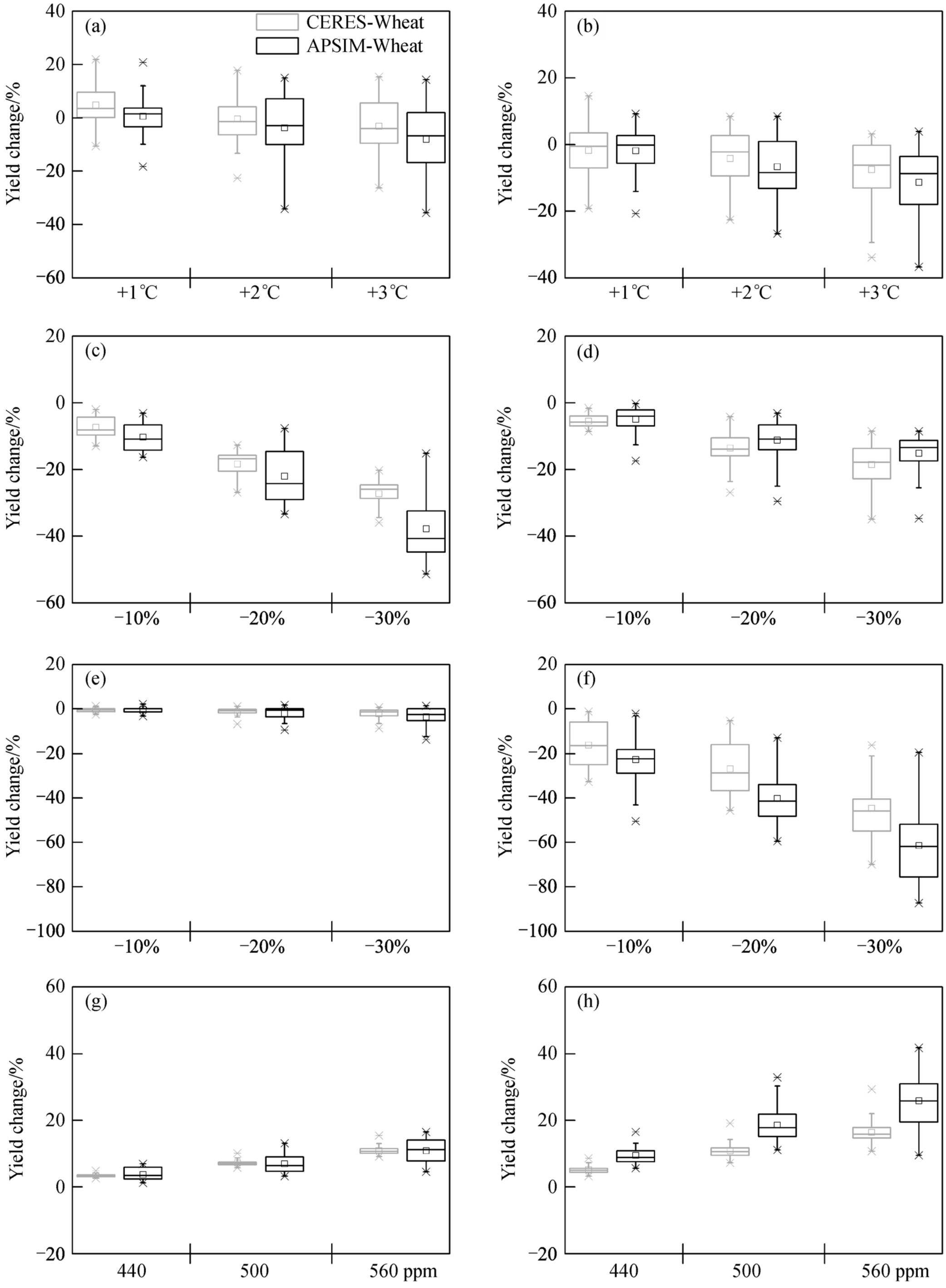

Fig. 4 CERES-Wheat and APSIM-Wheat model-simulated winter wheat yield sensitivity to mean temperature (a, b), radiation (c, d), precipitation (e, f), and CO_2 concentration (g, h) under well-irrigated (a, c, e, g) and rain-fed (b, d, f, h) conditions at Luancheng Agro-experimental Station in the North China Plain. The upper and lower hinges of the box plots denote the 75th and 25th percentiles of the respective data sets. The in-box lines denote median values, and open squares denote mean values of the respective datasets.

(2003) found that wheat yield increased linearly with CO_2 at a rate of 10%–16% per 100 ppm from 350 ppm up to 700 ppm. This study showed that wheat yield under well-irrigated CFG conditions linearly increased by ≈3.5% per 60 ppm increase in CO_2 concentration from 380 ppm to 560 ppm. Winter wheat yield under rain-fed YY condition increased linearly by ≈7.0% for the same increase in CO_2 concentration (Table 8).

Table 8 Average values for winter wheat yield sensitivity to climate variables of temperature, radiation, precipitation, and CO_2 concentration under well-irrigated (CFG) and rain-fed (YY) conditions in the North China Plain based on CERES-Wheat and APSIM-Wheat simulations

Climate variable	Treatment	CFG			YY		
		CERES-Wheat	APSIM-Wheat	Average	CERES-Wheat	APSIM-Wheat	Average
Temperature	+1°C	(4.2±7.7)%	(0.6±7.4)%	2.4%	(−1.8±7.6)%	(−1.9±7.3)%	−1.8%
	+2°C	(−0.4±8.8)%	(−3.7±13.1)%	−2.1%	(−4.2±8.1)%	(−6.6±8.7)%	−5.4%
	+3°C	(−3.1±10.3)%	(−8.0±12.3)%	−5.6%	(−7.5±9.0)%	(−11.3±10.5)%	−9.4%
Radiation	−10%	(−7.3±3.0)%	(−10.3±4.0)%	−8.8%	(−5.5±1.9)%	(−4.9±3.9)%	−5.2%
	−20%	(−18.4±4.3)%	(−22.0±7.8)%	−20.2%	(−13.6±4.3)%	(−11.2±5.6)%	−12.4%
	−30%	(−27.3±4.3)%	(−37.8±9.6)%	−32.5%	(−18.6±6.1)%	(−15.1±6.4)%	−16.9%
Precipitation	−10%	(−0.6±1.0)%	(−0.3±1.4)%	−0.4%	(−16.2±9.4)%	(−22.8±10.3)%	−19.5%
	−20%	(−1.4±2.0)%	(−1.9±2.6)%	−1.7%	(−26.9±11.8)%	(−40.2±11.5)%	−33.6%
	−30%	(−2.2±2.5)%	(−3.5±4.2)%	−2.8%	(−44.7±15.5)%	(−61.4±16.2)%	−53.1%
CO_2	440 ppm	(3.3±0.4)%	(3.7±1.8)%	3.5%	(5.1±1.0)%	(9.4±2.6)%	7.3%
	500 ppm	(7.2±0.8)%	(6.9±2.7)%	7.0%	(10.8±2.3)%	(18.5±5.2)%	14.7%
	560 ppm	(10.8±1.2)%	(10.9±3.7)%	10.9%	(16.4±3.6)%	(25.9±7.5)%	21.1%

Note that "±number" is the standard error of the difference (SED) of respective variables; CFG denotes four times of irrigation, and YY is rain fed.

4 Conclusions

The impact of climate change on crop yield depends not only on the degree of climate change but also on the degree of adaption of agricultural processes to climate change. Model analysis of the sensitivity of crop yield to climate change deepens our understanding of the processes of crop production in the face of changing climatic conditions, and thereby strengthens our food security. The two model simulations were consistent, and suggested that changes in climatic variables affect wheat production under different water conditions. There is therefore the need to develop and prioritize crop adaptation strategies to support sustainable food security in the study area.

The approach adopted in this study was limited by limitations in the CERES-Wheat and APSIM-Wheat crop models. Like several other models, CERES-Wheat and APSIM-Wheat are built on some fundamental assumptions and simplified real-world situations. The models do not simulate extreme soil conditions (e.g., soil salinity, acidity, and compaction) or weather events (e.g., floods, tornadoes, hurricanes, hail storms, droughts). Also, the model simulation in this study did not take into account the effects of diseases, pest damages, or weed competition on crop yield. The wheat cultivar used was assumed to be tolerant to climate change under the base-run conditions.

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