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Application of the CSM–CERES–Wheat Model for Yield Prediction and Planting Date Evaluation at Guanzhong Plain in Northwest China

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ABSTRACT

Water is the most important limiting factor for winter wheat (*Triticum aestivum* L.) production on the Guanzhong Plain in Northwest China. It is important to develop water management practices by knowing when to irrigate and how much water should be applied. The impact of different irrigation conditions on crop production can be analyzed with crop simulation models. The objectives of this study were (i) to evaluate the performance of the Cropping System Model (CSM)–CERES–Wheat model for simulating the impact of different irrigation regimes on winter wheat growth, development, and grain yield, and (ii) to determine the optimum sowing dates for irrigated and rainfed winter wheat grown under semiarid conditions using the CSM–CERES–Wheat model. Data were obtained from two experiments with three irrigation levels that were conducted under both field conditions and controlled conditions in a rain-out shelter in Yangling, Shaanxi Province of China, during the 2011–2012 and 2012–2013 growing seasons. The simulation results showed that the model performed well, as indicated by a close correspondence of simulated crop phenology, final aboveground biomass, leaf area index, and grain yield with observed data. The model was inaccurate in simulating winter wheat biomass under stressed conditions. The normalized root mean square error was <2% for phenology, 15.4% for final aboveground biomass, and 14.8% for grain yield. The sowing date analysis showed that a delayed sowing date from 7 September to 27 October caused a decrease in the average yield of 36.7% for all the rainfed and irrigated scenarios. The optimum sowing date was determined to be 7 October for the local farming system.

Core Ideas

- CSM-CERES-Wheat model simulated different irrigation regimes under shield and field conditions.
- Simulated and measured phenology, LAI, total biomass, and grain yield agreed well.
- The model was not suitable as a tool to determine the optimum sowing date.
- High density and medium irrigation was the best management practice for wheat.

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Globally, the availability of water is the main limitation for crop growth and development and can lead to a substantial loss of crop yield for many regions (Eck, 1986; Ehdaie, 1995; Lamb et al., 2011). Winter wheat is one of the main food crops on the Guanzhong Plain in Shaanxi Province of northwestern China, which is a very important national agricultural production region. Located on the edge of the continental monsoon climate zone, the Guanzhong Plain is a climate-sensitive region and its annual precipitation varies greatly. Therefore, it is common for drought stress to occur during the growing season in this region, which constrains wheat production (Huang et al., 2014). Farmers apply irrigation during drought periods to maintain yield and sustain profitable crop production. Similar to many regions across the world, irrigation management in the field is a complex problem due to the high spatial and temporal variability of local weather conditions, soil characteristics, including the ability of the soil to hold water, and crop water requirements (Farré and Faci, 2009; Salazar et al., 2012; Sun et al., 2006). The uncertainty of the occurrence of drought and the type of drought will govern optimal crop management schemes (Blum, 2009; Debaeke and Aboudrare, 2004; Geerts and Raes, 2009). Usually, wheat varies in its response to water deficit at different growth stages, and the amount of water applied is closely related to the final biomass and grain yield (Iqbal et al., 2014; Wang et al., 2013; Zhang et al., 2006). However, it is difficult to study the proper management practices suitable for water-limited conditions for individual crops or locations through labor-intensive, time-consuming, and costly field experiments. Consequently, tools are needed that can extrapolate results beyond experimental conditions and can integrate knowledge about soil, climate, crop, and field management to make better decisions about transferring production technology from one location to others where the soils and weather conditions are different.

Crop simulation models have been used as a multipurpose tool for a diverse range of applications in many countries (Boote

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Abbreviations: CSM, Cropping System Model; ET, evapotranspiration; IWUE, irrigation water use efficiency; LAI, leaf area index; NRMSE, normalized root mean square error; WUE, water use efficiency.

et al., 1996; Hoogenboom, 2000). For example, applications include the simulation of the potential impacts of climate change and global warming on yield, resource utilization, and the environment and to develop mitigation strategies under climate change (Alexandrov and Hoogenboom, 2000; Jones and Thornton, 2003), determination of optimum planting dates (Mall et al., 2004; Ruíz-Nogueira et al., 2001; Soler et al., 2007), evaluation of crop responses to environmental stresses to identify alternate irrigation regimes for specific scenarios (Guerra et al., 2007; Heinemann et al., 2002; Nijbroek et al., 2003), and prospective deficit irrigation strategies (Heng et al., 2007; Liu et al., 2007; Pereira et al., 2009).

In the case of wheat, the process-oriented Cropping System Model (CSM)–CERES (Crop Estimation through Resource and Environment Synthesis)–Wheat has been developed and included in the Decision Support System for Agrotechnology Transfer (DSSAT Version 4.6) (Hoogenboom et al., 2010, 2011; Jones et al., 2003), which is a comprehensive decision support system that can be used for various applications, ranging from basic decision support management to advancing understanding of agricultural research, such as yield and water use predictions (Garrison et al., 1999; Sinclair and Seligman, 1996). The CSM–CERES–Wheat model has been widely used to assess cropping and management strategies for wheat (both rainfed and irrigated) for more than two decades in many countries (Langensiepen et al., 2008; Savin et al., 1995; Timsina et al., 2008; Timsina and Humphreys, 2006). Specifically, this model can be used to describe the wheat response under different soil and weather conditions and genetic interactions (Arora et al., 2007; Dettori et al., 2011; Hundal and Kaur, 1997; Pecetti and Hollington, 1997).

Since its release, the CERES–Wheat model has been widely studied in China (He et al., 2013; Ji et al., 2014). Yang et al. (2006) found the optimum irrigation scheme for winter wheat with the model to show the drawdown of groundwater in the piedmont region of the Thihang Mountains on the North China Plain. Xiong et al. (2008) evaluated the performance of CERES–Wheat by simulating the regional spatial and temporal characteristics of wheat production in China. Hu et al. (2009) used the CSM–CERES–Wheat model to analyze the effect of different irrigation regimes on grain yield, evapotranspiration, and water use efficiency of winter wheat on the North China Plain. However, there are only a few studies that have been conducted in the Guanzhong Plain where the yield is often limited by moisture deficit (Tang et al., 2013). The overall goal of this study was the application of the CSM–Wheat model for yield prediction and planting date evaluation on the Guanzhong Plain in Northwest China. The specific objectives were (i) to evaluate the performance of the CSM–CERES–Wheat model for simulating the growth, development, and yield of wheat, and (ii) to determine the optimum sowing dates for wheat yield under irrigated and rainfed conditions using the CSM–CERES–Wheat model.

MATERIALS AND METHODS

Field Experiments

Field experiments were conducted at the Key Laboratory of Agricultural Soil and Water Engineering in Arid Area of the Ministry of Education (34°18′ N, 108°24′ E), at Northwest A&F University, Yangling, Shaanxi Province, China. The site is located in a semiarid climate zone with a mean annual precipitation of 548 mm and mean annual temperature of 12.9°C. The local soil texture is silty clay loam, and the soil characteristics and parameters are shown in Table 1. The experiments were conducted in two parts, i.e., under field conditions and under a rain-out shelter, from October to June during the 2011–2012 and 2012–2013 winter wheat growing seasons. A widely used winter wheat cultivar in Shaanxi Province, Xiaoyan 22, was planted manually at a row spacing of 20 cm. Wheat was planted on 19 Oct. 2011 and on 18 Oct. 2012 under the shelter and on 17 Oct. in both 2011 and 2012 under field conditions and was harvested during June in the following year. Fertilizer was applied as urea for all the treatments for both experimental sites at a rate of 60 kg N ha^{-1} at planting and then with the first irrigation at a rate of 60 kg N ha^{-1} during the growing season based on estimated plant growth. Weeds were effectively controlled using herbicides and with hand weeding, while fungicides and pesticides were applied as needed during the growing season.

The experiment under the large mobile rain-out shelter (48 m long by 10 m wide by 4 m high) was performed in 27 3.33- by 2-m experimental plots that were separated by 25-cm-thick concrete walls (3 m in depth), and the bottom of each plot was also lined with concrete. The treatments were randomly arranged. The cover of the shelter was made of plastic and could be moved along tracks using a remote control. The shelter was closed during rainy and snowy days and kept open during dry days to maintain the same weather conditions as in the surrounding fields. The sowing density was 640 seeds m^{-2}. The irrigation application levels were scheduled as 100% (high), 80% (medium), and 60% (low) of winter wheat evapotranspiration (ET). Evapotranspiration was measured with two large weighing lysimeters with continuous electronic data reading devices installed in two experimental plots. The dimensions of the lysimeters were 3 m long by 2.2 m

Table 1. Physical and chemical properties of the soil at five depths at the experimental site in Yangling, Shaanxi Province, China.

Soil property	0–23 cm	23–35 cm	35–95 cm	95–196 cm	196–250 cm
Texture	silty clay loam	silty clay loam	silty clay loam	silt loam	silty clay loam
Sand, %	26.71	24.98	24.11	21.32	30.64
Silt, %	50.85	52.78	54.75	48.60	47.55
Clay, %	22.10	22.10	20.90	30.10	21.60
Bulk density, g cm^{-3}	1.32	1.40	1.41	1.36	1.32
Organic matter, %	1.17	0.65	0.55	0.64	0.39
Total N, % (w/w)	0.09	0.06	0.05	0.05	0.03
Total P, % (w/w)	0.02	0.02	0.02	0.01	0.01
Total K, % (w/w)	1.74	1.25	1.20	1.39	1.75
pH	8.00	8.20	8.20	8.20	8.20

wide by 3 m deep, the range of the lysimeters was 0 to 6 t with a deviation of ±1%, and the sensitivity was <150 g. The lysimeters received the high irrigation level. Crop management and soil conditions in the lysimeters were the same as in the other experimental plots. There were nine treatments for each year's experiment, and the irrigation schedules were based on four growth stages, i.e., winter, tillering, jointing, and anthesis. Each treatment was replicated three times. However, there were only three irrigation events in 2011–2012 (Table 2).

The open field experiment was 200 m from the rain-out shelter. It also included nine treatments, which were randomly arranged, consisting of three irrigation levels and three planting densities, with two replications per treatment in both years. Each experimental plot was 5 by 3.5 m; furrow irrigation was supplied to the plots from a pump outlet using 10-cm-diameter plastic pipes, and a flow meter was used to measure the amount of water applied. Planting density in the different treatments was at rates of 715 (high), 570 (medium), and 428 (low) seeds m^{-2} in the 2011–2012 growing season and 810 (high), 570 (medium), and 333 (low) seeds m^{-2} in the 2012–2013 growing season. Generally, there was some rainfall after planting. Therefore, we applied only three irrigation events for the field experiment. The irrigation level was the same as under the shelter in the first year (2011–2012), while in the second year (2012–2013), we eliminated the medium irrigation level and added a rainfed treatment (Table 2).

Plant Measurements

Plant samples were taken every 7 to 10 d during the growing season from the tillering stage to maturity. A sample of 10 plants was taken from the middle of each plot, and the fresh mass of leaf, stem, and spike was measured. Then the partitioned samples were oven dried at 75°C for 48 h to obtain the dry partitioning biomass. Leaf area index (LAI) was measured six times and five times for the shelter in 2011–2012 and 2012–2013, respectively, and four times and three times for the field in 2011–2012 and 2012–2013, respectively, during the growing season using a SunScan canopy analyzer (Delta-T Devices). When the plants reached physiological maturity, a 1-m^2 area was cut in the center of each experimental plot under the shelter and in the field to measure the final biomass and grain yield.

Soil and Weather Data

The basic soil hydraulic characteristics and initial conditions of soil parameters used in the present study were obtained from previous studies (Ji et al., 2014) (Table 3). The soil of the experimental site was a silty clay loam. Daily maximum and minimum air temperature, rainfall (Fig. 1), and sunshine hours were obtained from the Yangling meteorological station, which is located beside the open field experimental site and 200 m from the rain-out shelter. The rainfall during the 2011–2012 and 2012–2013 winter wheat growing seasons was 278.8 and 221.3 mm, respectively. Daily solar radiation was determined

Table 2. Irrigation levels applied as a percentage of evapotranspiration (ET) during different growth phases (winter, tillering, jointing, and anthesis) for the 2011–2012 and 2012–2013 growing seasons for the shelter (top) and field (bottom) experiments.

Treatment†	2011–2012 Irrigation amount			Treatment	2012–2013 Irrigation amount			
	% of ET				% of ET			
	Shelter							
	30 Mar.	19 Apr.	30 Apr.		27 Dec.	15 Mar.	11 Apr.	4 May
HHH	100	100	100	HHHH	100	100	100	100
HMM	100	80	80	HMMM	100	80	80	80
HLL	100	60	60	HLLL	100	60	60	60
MML	80	80	60	MHML	80	100	80	60
MLH	80	60	100	MMLH	80	80	60	100
MHM	80	100	80	MLHM	80	60	100	80
LLM	60	60	80	LHLM	60	100	60	80
LHL	60	100	60	LMHL	60	80	100	60
LMH	60	80	100	LLMH	60	60	80	100

	Field							
	2011–2012				2012–2013			
	Planting density	Irrigation amount			Planting density	Irrigation amount		
		30 Mar.	19 Apr.	30 Apr.		15 Mar.	11 Apr.	4 May
	seeds m^{-2}	% of ET			seeds m^{-2}	% of ET		
$PD_1 + W_H$	715	100	100	100	810	100	100	100
$PD_1 + W_M$	715	80	80	80	810	60	60	60
$PD_1 + W_L$	715	60	60	60	810	0	0	0
$PD_2 + W_H$	570	100	100	100	570	100	100	100
$PD_2 + W_M$	570	80	80	80	570	60	60	60
$PD_2 + W_L$	570	60	60	60	570	0	0	0
$PD_3 + W_H$	428	100	100	100	333	100	100	100
$PD_3 + W_M$	428	80	80	80	333	60	60	60
$PD_3 + W_L$	428	60	60	60	333	0	0	0

† H, high irrigation level; M, medium irrigation level; L, low irrigation level; PD_1, high planting density; PD_2, medium planting density; PD_3, low planting density; W, irrigation water.

Table 3. Soil hydraulic characteristics and initial conditions of the soil profile for the winter wheat experiments conducted in Yangling, Shaanxi Province, China (Ji et al., 2014).

Soil depth	Wilting point at −1500 kPa	Field capacity at −33 kPa	Saturation	Initial water content	NH_4–N conc.	NO_3–N conc.
cm	$cm^3\ cm^{-3}$				$g\ Mg^{-1}$	
0–5	0.10	0.28	0.45	0.28	1.90	12.90
5–35	0.11	0.28	0.46	0.24	0.50	11.20
35–70	0.12	0.28	0.46	0.22	0.40	12.60
70–90	0.14	0.28	0.49	0.22	0.60	11.80
90–100	0.14	0.28	0.50	0.23	0.60	10.50

based on the observed daylight sunshine hours through WGEN in the DSSAT Version 4.6 crop systems model.

Water Use Efficiency and Irrigation Water Use Efficiency

Winter wheat evapotranspiration, ETc, was calculated as

$$\mathrm{ETc} = I + P - R - D - \mathrm{SW} \qquad [1]$$

where ETc (mm) is the actual crop evapotranspiration of the treatments during the whole growing season, I (mm) is the amount of irrigation water, P (mm) is precipitation; R (mm) is the surface runoff, which was assumed to not be significant because concrete walls were placed around each plot for the rain-out shelter experiment and borders existed in each plot for the open field experiment; D (mm) is the downward flux below the crop root zone, which was ignored because the bottom of each plot was impermeable in the rain-out shelter, and the soil's field capacity was not exceeded during irrigation for the open field experiment; and SW (mm) is the change in soil water storage.

Water use efficiency for grain yield (WUE, kg ha^{-1} mm^{-1}) for winter wheat was calculated as

$$\mathrm{WUE} = \frac{Y}{\mathrm{ETc}} \qquad [2]$$

where Y (kg ha^{-1}) is grain yield.

Irrigation water use efficiency for grain yield (IWUE, kg ha^{-1} mm^{-1}) was calculated as

$$\mathrm{IWUE} = \frac{Y_{irr} - Y_{rain}}{I} \qquad [3]$$

where Y_{irr} (kg ha^{-1}) is grain yield under irrigated conditions, Y_{rain} (kg ha^{-1}) is grain yield under rainfed conditions, and I (mm) is the irrigation amount.

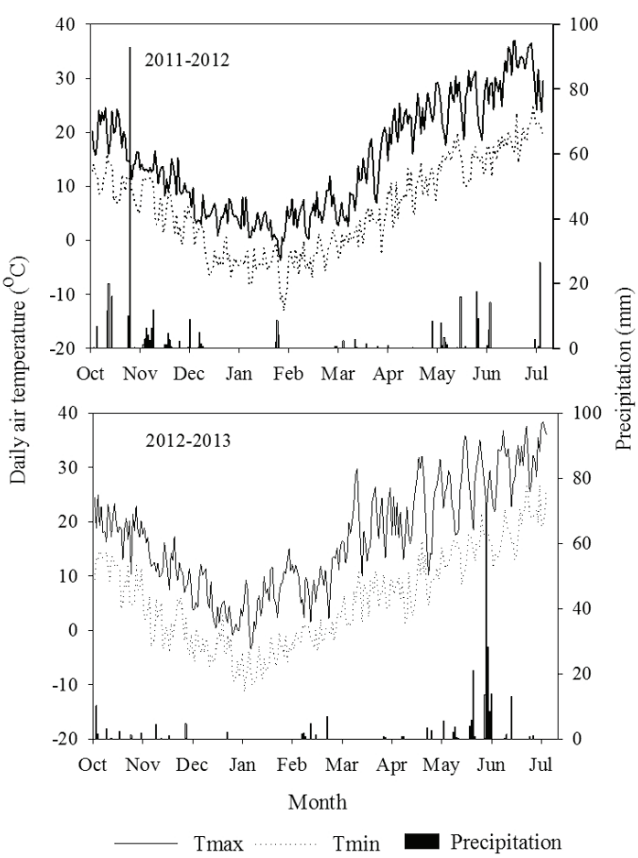

Fig. 1. Daily maximum and minimum temperature (Tmax and Tmin, respectively) and precipitation during the growing seasons of 2011–2012 and 2012–2013 at the experimental site.

CSM-CERES-Wheat model

The CSM–CERES–Wheat is part of the DSSAT–CSM (Jones et al., 2003, 2010). It is a physiological-process-based model that simulates growth and development throughout the growing season from planting to harvest. It simulates the effects of weather, genotype, soil properties (water and N), and management on crop growth and development with a daily time step under variable climate and environmental conditions. The daily biomass accumulation is determined by converting daily photosynthetically active intercepted radiation using a crop-specific radiation use efficiency parameter (Ritchie et al., 1998). The daily grain growth rate is based on the interaction of temperature, grains per plant, potential kernel growth rate, soil moisture, and N effect on growth (Ritchie et al., 1998), ultimately resulting in the final yield.

Calibration of the Cultivar Coefficients

Prior to evaluation of a model, it is essential to determine the cultivar coefficients for the local cultivars. The cultivar coefficients for Xiaoyan 22 winter wheat were estimated with the data from four full irrigation treatments (treatment HHH under the shelter in 2011–2012, treatment HHHH under the shelter in 2012–2013, and the medium-density treatment $PD_2 + W_H$ in the field). For the open field experiment, the medium planting density of the full irrigation treatment was selected because of the similar planting density to the treatments under the shelter. The CSM–CERES–Wheat model includes seven cultivar coefficients that define the growth and development characteristics or traits

Table 4. Genetic coefficients for the wheat cultivar Xiaoyan 22 calibrated with the data from the non-stress treatments of the experiments conducted during the 2011–2012 and 2012–2013 growing seasons.

Coefficient	Value
Time at optimum vernalizing temperature required to complete vernalization (P1V), d	6.62
Reduction in development rate in a photoperiod 10 h shorter than the threshold relative to that at the threshold (P1D), %	81.37
Grain filling (excluding lag) phase duration (P5), °C d	572.10
Kernel number per unit canopy weight at anthesis (G1), no. g^{-1}	23.30
Potential kernel growth rate (G2), mg d^{-1}	33.70
Standard, non-stressed dry weight (total, including grain) of a single tiller at maturity (G3), g	1.55
Thermal time between the appearance of leaf tips (PHINT), °C d	97.20

of a wheat cultivar. Cultivar coefficients in the calibration were obtained sequentially, starting with phenological development parameters related to flowering and maturity dates (P1V, vernalization; P1D, photoperiod; P5, grain-filling duration; and PHINT, the interval between successive leaf tip appearances) followed by the crop growth parameters related to the kernel filling rate and kernel numbers per plant (G1, kernel number; G2, kernel size; and G3, dry weight) (Hunt and Boote, 1998). The trial and error method was used to determine genetic coefficients computationally (Mavromatis et al., 2001), and each cultivar coefficient was estimated by repeated iterations during the model calculations. The calibration procedure was stopped when a close match between simulated and observed phenology, aboveground biomass, and yield (within the range of values for ±2 d, ±10%, and ±15%, respectively) were obtained. A detailed description of the winter wheat cultivar Xiaoyan 22 coefficients used by CSM–CERES–Wheat model is presented in Table 4.

Performance Evaluation of the Model

The experimental data for winter wheat in 2011–2012 and 2012–2013 from both experimental sites, that were not used in the model calibration were used for the performance assessment of the calibrated CSM–CERES–Wheat model. The evaluation was conducted by comparing the simulated values of development and growth characteristics with the corresponding observed values (average value of all the replications for each treatment) and by evaluating various statistics, which included the index of agreement (d) (Timsina et al., 2008; Yang et al., 2014) and the normalized root mean square error (NRMSE) (Anothai et al., 2013; Dettori et al., 2011; Timsina and Humphreys, 2006). The NRMSE gives a normalized value that allows averaging across multiple characteristic targets, providing a single index for their goodness of fit. The NRMSE was expressed as a percentage, which is desired to define a good fit by having a low value. According to the d statistic, the closer the index value is to one, the better the agreement between the two variables. The value of NRMSE and the d statistic were calculated as

$$\mathrm{RMSE}=\sqrt{\frac{\sum_{i=1}^{n}\left(P_i-O_i\right)^2}{n}} \qquad [4]$$

$$\mathrm{NRMSE}=\frac{\mathrm{RMSE}\times 100}{\bar{O}} \qquad [5]$$

$$d=1-\left[\frac{\sum_{i=1}^{n}\left(P_i-O_i\right)^2}{\sum_{i=1}^{n}\left(\left|P_i'\right|+\left|O_i'\right|\right)^2}\right] \qquad 0\le d\le 1 \qquad [6]$$

where n is the number of observations; P_i is the ith simulated value, O_i is the ith observed value; $\bar{O}$ is the overall mean of observed values; $P_i' = P_i - \bar{O}$; and $O_i' = O_i - \bar{O}$. The simulation is considered excellent when the NRMSE is <10%, good if the NRMSE is >10% and <20%, fair if NRMSE is >20% and <30%, and poor if the NRMSE is >30% (Jamieson et al., 1991).

Application of the Model for Sowing Date

An analysis of the effect of different sowing dates on grain yield, irrigation amount, ET, WUE, and IWUE of the winter wheat was conducted using 30 yr of historical weather data from 1984 to 2013. Simulations were conducted using only conditions representing the open field experiment. Seven different sowing dates were simulated using the seasonal analysis tool (Thornton et al., 1995, 1998) of DSSAT Version 4.6 under different planting densities and irrigation conditions. The overall goal was to determine the optimum sowing dates for winter wheat on the Guanzhong Plain. However, the level of rainfall varied every year and it is not possible to set a fixed irrigation date and amount, and so the irrigation management was set to automatic irrigation during the simulation. Thus, for the high irrigation level, automatic irrigation was set to when the soil water content dropped below 80% of field capacity, while the medium irrigation level was set to irrigate when the soil water content dropped to 50% of field capacity at a depth of 50 cm, and the low irrigation level was set as rainfed. The soil characteristics, fertilizer application, and other required model parameters (e.g., row spacing, seeding depth) were the same as those for the field experiment. The earliest sowing date was 27 August, and there were subsequent sowings every 10 d until 27 October. The simulation results were presented in box plots, in which the box itself contains the middle 50% of the data, the upper quartile of the box indicates the 75th percentile of the data set, and the lower quartile indicates the 25th percentile. The horizontal line inside the box indicates the median yield. The upper adjacent and lower adjacent lines of the diagram represent the yield between the 10th and 90th percentiles.

Table 5. Comparison between simulated (Sim.) and observed (Obs.) anthesis and maturity dates, final yield, and total biomass for the experiments conducted during the 2011–2012 and 2012–2013 growing seasons in Yangling, Shaanxi Province, China. The treatments used in the calibration were the full irrigation treatments from the 2011–2012 and 2012–2013 rain-out shelter experiment and the medium planting density, full irrigation treatment from the 2011–2012 and 2012–2013 open field experiment.

		Anthesis date		Maturity date		Biomass		Yield	
Exp.	Season	Sim.	Obs.	Sim.	Obs.	Sim.	Obs.	Sim.	Obs.
						t ha^{-1}			
Shelter	2011–2012	5 May	2 May	8 June	6 June	14.85	14.40 ± 2.9	6.91	8.10 ± 0.2
	2012–2013	29 Apr.	30 Apr.	2 June	3 June	15.69	16.33 ± 0.1	7.92	7.03 ± 0.5
Field	2011–2012	6 May	1 May	9 June	6 June	14.59	14.05 ± 0.1	6.67	6.60 ± 0.1
	2012–2013	29 Apr.	29 Apr.	3 June	3 June	15.14	13.76 ± 0.3	7.49	8.80 ± 0.2

RESULTS

Calibration of the Cultivar Coefficients

A close agreement was obtained between observed and simulated values for winter wheat phenology and growth. The calibrated model predicted days from planting to anthesis with a mean difference of 3 d for the 2011–2012 shelter experiment, 1 d for the 2012–2013 shelter experiment, and 5 d for the 2011–2012 and 2012–2013 field experiments (Table 5). The difference between simulated and observed days from planting to maturity for the calibrated model was less than for anthesis: 2 d for the 2011–2012 shelter experiment, 1 d for the 2012–2013 shelter experiment, and 3 d for the 2011–2012 and 2012–2013 field experiments (Table 5). There was good agreement between the simulated and observed biomass at maturity for the two experiments for both growing seasons, with an absolute difference of <10%. The difference between simulated and observed grain yield was larger, and the absolute difference was <15% (Table 5).

The simulated values and corresponding observed values for in-season stem and total biomass for the calibration were in good agreement with the observed data for both growing seasons, with an example illustrated in Fig. 2. The total biomass had an NRMSE that ranged from 21 to 38%, while the leaf biomass had an NRMSE that ranged from 57 to 109% and the stem biomass had an NRMSE that ranged from 29 to 43% (Table 6). Despite some discrepancies, the overall results for total biomass, with a

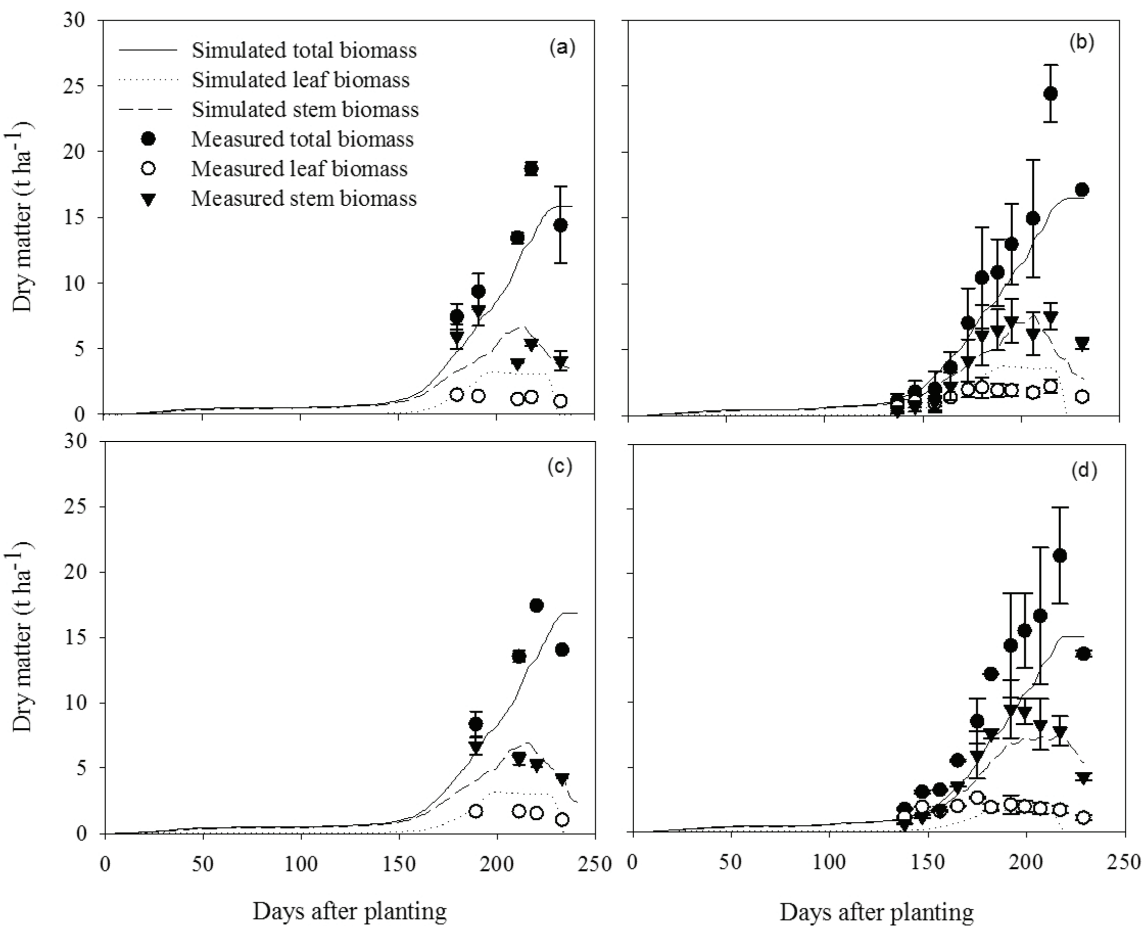

Fig. 2. A comparison between simulated and observed values for model calibration of total aboveground, leaf, and stem biomass for the full irrigation treatments of two experiments conducted during the 2011–2012 and 2012–2013 growing seasons: (a) 2011–2012 rain-out shelter experiment; (b) 2012–2013 rain-out shelter experiment; (c) medium planting density for the 2011–2012 field experiment; and (d) medium planting density for the 2012–2013 field experiment.

Table 6. The normalized root mean square error (NRMSE) and index of agreement (*d*) for model calibration with time series data for crop characteristics of winter wheat grown under a rain-out shelter and in the field during the 2011–2012 and 2012–2013 growing seasons.

		Total biomass		Leaf biomass		Stem biomass	
Exp.	Season	NRMSE	*d*	NRMSE	*d*	NRMSE	*d*
		%		%		%	
Shelter	2011–2012	25.4	0.86	108.6	0.21	43.0	0.91
	2012–2013	37.9	0.90	75.0	0.63	31.7	0.91
Field	2011–2012	20.8	0.81	76.5	0.46	35.8	0.38
	2012–2013	38.3	0.88	57.4	0.49	29.2	0.92

main NRMSE of 31%, and stem biomass, with a main NRMSE of 35%, indicated better agreement between simulated and observed values for these traits than for leaf dry mass. However, the high NRMSE values for leaf biomass were caused by considerable leaf losses due to late leaf spot disease (*Cladosporium herbarum*), even though pesticides were applied. The model did not simulate these leaf losses.

Performance Evaluation of the CSM–CERES–Wheat Model

The performance of the CSM–CERES–Wheat model was evaluated with the data sets obtained from both shelter and field experiments for both growing seasons that were not used for model calibration. The variables that were evaluated included crop phenology, in-season biomass, LAI, total aboveground biomass at maturity, and grain yield.

Phenology, Aboveground Biomass, and Grain Yield

The CSM–CERES–Wheat model was able to simulate the winter wheat phenology during the growing seasons in good agreement with the observed data. There was a close match between simulated and observed days from planting to anthesis and from planting to physiological maturity. The coefficient of determination (r^2) between the simulated and observed days from sowing to anthesis for the two growing seasons in the two experiments had a high value of 0.85 and the NRMSE had a low value of 1.5%. Similarly, the evaluation for simulating the days from sowing to maturity also showed a high r^2 value of 0.98 and a low NRMSE value of 0.8% (Fig. 3).

The RMSE for total biomass between simulated and measured values was 2.15 t ha^{-1} and the NRMSE was 15.4%. The grain yield, however, was slightly and consistently overestimated. The RMSE between simulated and measured grain yield was 0.92 t ha^{-1}

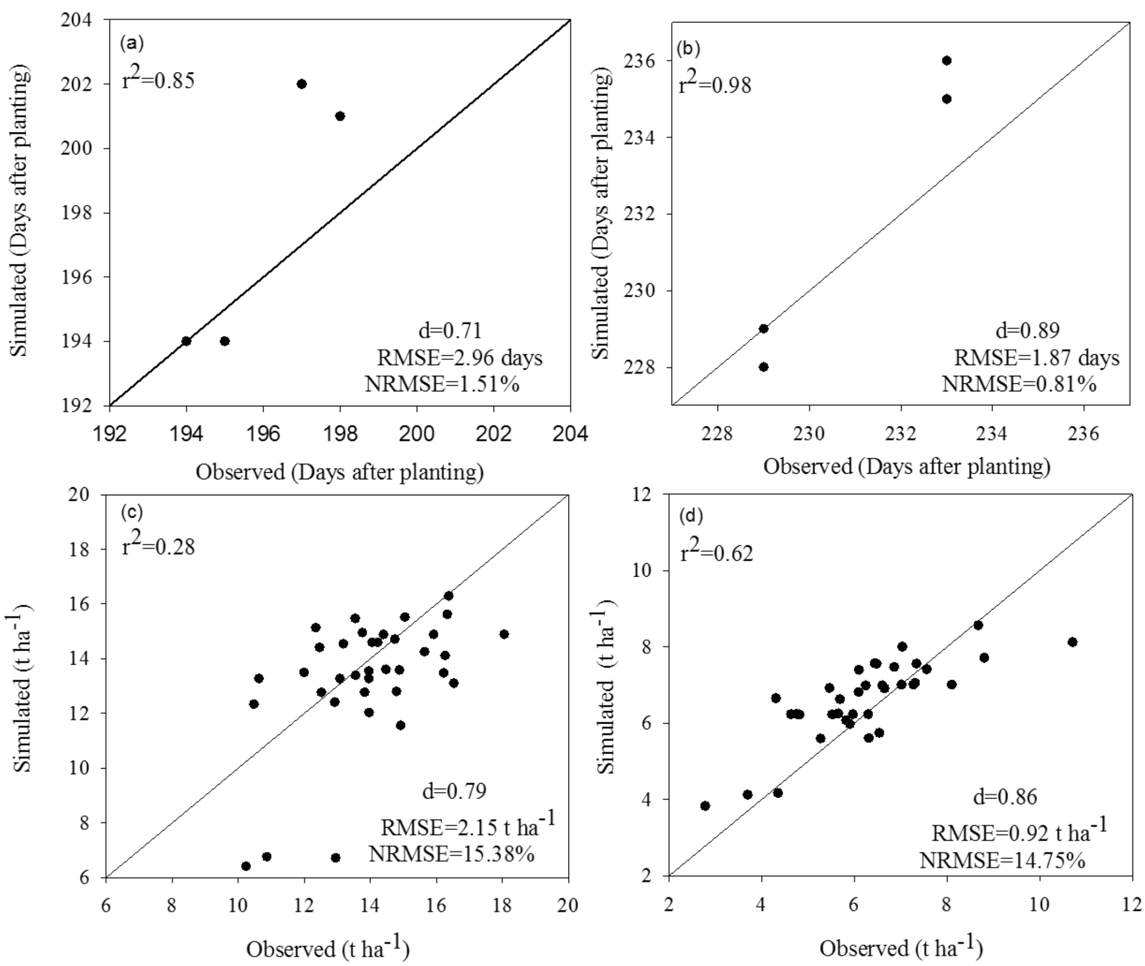

Fig. 3. A comparison between simulated and observed values for model evaluation of (a) anthesis date, (b) maturity date, (c) final aboveground biomass, and (d) grain yield of winter wheat grown during the 2011–2012 and 2012–2013 growing seasons.

and the NRMSE was 14.8%. Although the NRMSE between simulated and measured values of biomass and grain yield was a little higher than for the simulation of anthesis and maturity, the results still indicated good agreement between simulated and observed values for the two growing seasons of winter wheat.

Leaf Area Index and In-Season Biomass

The performance evaluation of LAI prediction with the CSM–CERES–Wheat model using the data from the 2011–2012 shelter experiment showed that the best prediction was for the LLM treatment that had an NRMSE of 17.5% and *d* value of 0.90 (Fig. 4). Values corresponding to the 2012–2013 growing season and for the field experiments are not shown because these were close to those corresponding to the 2011–2012 shelter experiment. For the 2012–2013 shelter experiment, LAI was not very well simulated, with the lowest NRMSE for the LMHH treatment of 22.5% and a *d* value of 0.89. For the 2011–2012 field experiment, the best prediction was for the $PD_1 + W_L$ treatment, with an NRMSE of 11.0% and a *d* value of 0.86. For the 2012–2013 field experiment, the LAI was also not very well simulated, showing the lowest NRMSE in the $PD_3 + W_L$ treatment of 16.3%. However, the CERES–Wheat model simulated LAI very well for the 2011–2012 field experiment, with a mean NRMSE of 15.4%, followed by a fairly

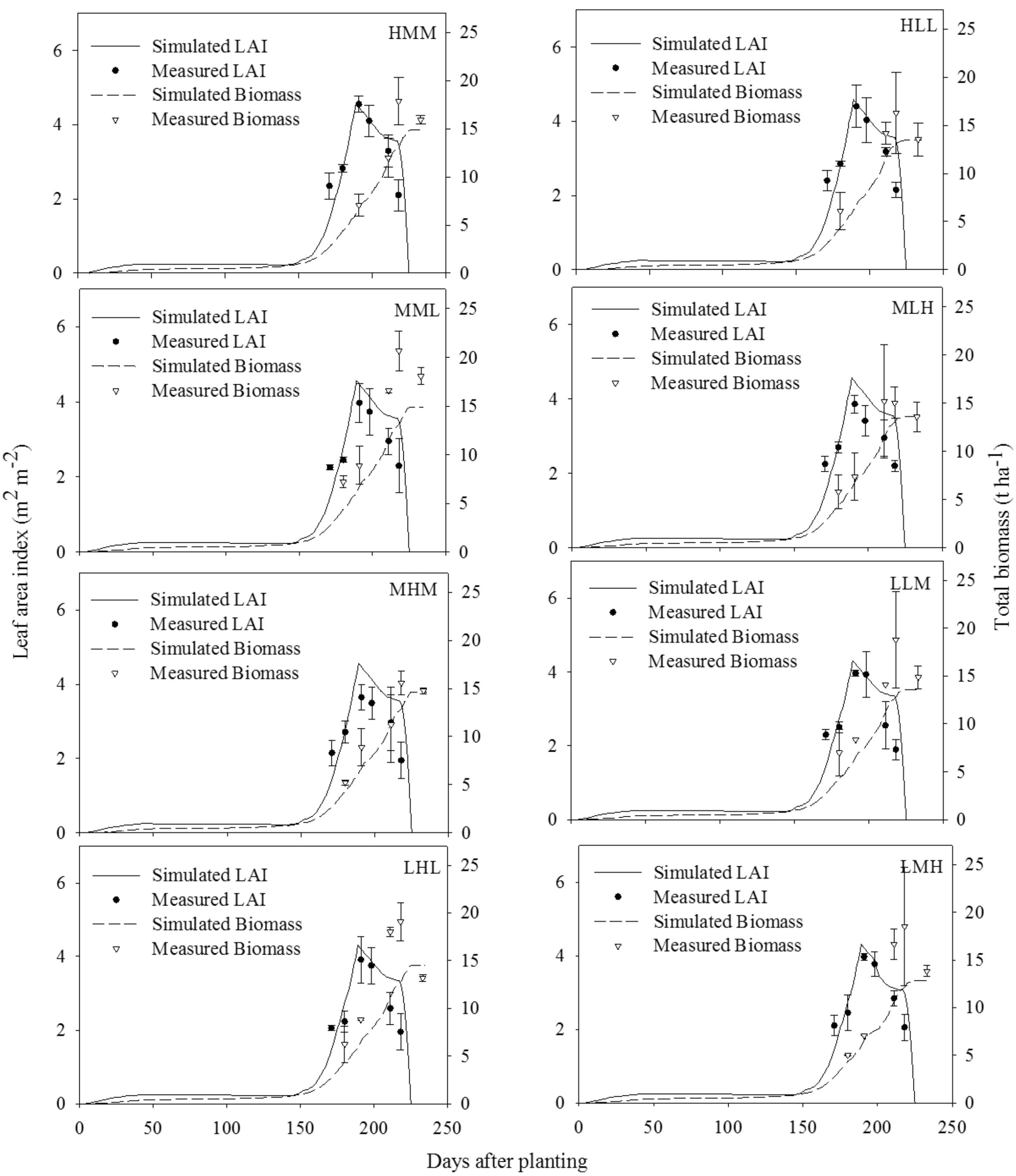

Fig. 4. A comparison between simulated and observed values for model evaluation of in-season biomass and leaf area index (LAI) for the shelter experiment during the 2011–2012 growing season; H, M, and L denote high, medium, and low irrigation amounts, respectively, for the three irrigations applied during the season.

Table 7. Simulated and observed water use efficiency (WUE) for winter wheat under a rain-out shelter and in the field during the 2012–2013 growing season in Yangling, Shaanxi Province, China.

Rain-out shelter			Field		
	WUE			WUE	
Treatment†	Simulated	Observed	Treatment‡	Simulated	Observed
	——— kg ha^{-1} mm^{-1} ———			——— kg ha^{-1} mm^{-1} ———	
HHHH	21.33	19.60	$PD_1 + W_H$	20.06	17.50
HMMM	24.43	19.90	$PD_1 + W_M$	20.04	25.90
HLLL	23.08	22.30	$PD_1 + W_L$	12.78	14.90
MHML	22.17	17.90	$PD_2 + W_H$	19.09	18.10
MMLH	23.49	22.90	$PD_2 + W_M$	19.11	17.80
MLHM	23.49	24.10	$PD_2 + W_L$	13.39	11.40
LHLM	23.71	19.70	$PD_3 + W_H$	16.88	11.00
LMHL	21.44	23.40	$PD_3 + W_M$	17.20	12.10
LLMH	21.60	17.10	$PD_3 + W_L$	14.11	9.10
Mean	22.75	20.77		16.96	15.31

† H, high irrigation amount; M, medium irrigation amount; L, low irrigation amount.

‡ PD_1, high planting density; PD_2, medium planting density; PD_3, low planting density; W_H, high irrigation amount; W_M, medium irrigation amount; W_L, low irrigation amount.

good simulation for the 2011–2012 shelter experiment, with a mean NRMSE of 23.4%, then a little high NRMSE for the 2012–2013 field and shelter experiments of 34.2 and 36.1%, respectively. In general, LAI was overestimated for most of the experiments during the two growing seasons, except for the three rainfed treatments in the 2012–2013 field experiment.

In addition, the results showed that LAI was highly influenced by the water amount, especially in the field experiment, e.g., treatments with medium and low water amounts had a significantly reduced LAI compared with treatments that had a high irrigation level. In general, LAI was very well simulated for the different planting density treatments, with a significant reduction of LAI values as the planting density decreased.

Similarly, the CSM–CERES–Wheat model simulated the in-season biomass fairly well for the 2011–2012 shelter experiment and 2011–2012 field experiment. The NRMSE for the shelter experiment ranged from 14.2% (MLH) to 33.9% (LMH) and had *d* values that ranged from 0.78 to 0.96 for all growth traits (Fig. 4). For the 2011–2012 field experiment, in-season biomass had an NRMSE that ranged from 15.0% ($PD_1 + W_H$) to 25.9% ($PD_3 + W_L$) and had *d* values that ranged from 0.67 to 0.85. However, the values for NRMSE were comparatively higher in 2012–2013 than in 2011–2012. For the 2012–2013 shelter experiment, in-season biomass had high to moderately high NRMSE, ranging from 33.4% (LLMM) to 50.2% (MHMM), and had moderately high *d* values, ranging from 0.79 to 0.91 (data not shown). For the 2012–2013 field experiment, the NRMSE ranged from 29.7% ($PD_2 + W_M$) to 65% ($PD_1 + W_L$) and the *d* values ranged from 0.64 to 0.93. In general, the overall results for in-season biomass were underestimated for all the experiments, which might have been caused by the following reasons: (i) the crop model reduced the biomass due to water stress during the simulation; or (ii) an error in counting planting density possibly occurred in the different growth stages that were used for biomass calculations.

Water Use Efficiency

The WUE of winter wheat under different irrigation conditions for both shelter and field experiments during the 2012–2013 growing season was estimated as grain yield per unit of ETc (Table 7). Values corresponding to the 2011–2012 growing season are not shown because of lack of soil water content data at the end of the growing season, which will lead to inaccuracy in calculating ETc. Thus, the error for the simulated and observed WUE values might be large. The measured WUE ranged from 17.1 to 24.1 kg ha^{-1} mm^{-1} for the shelter experiment and from 9.1 to 25.9 kg ha^{-1} mm^{-1} for the field experiment. Simulated WUE had a close agreement with the observed values, with an NRMSE of 14.6% and a *d* value of 0.91 for the shelter experiment and an NRMSE of 25.5% and a *d* value of 0.95 for the field experiment. Both the highest simulated and observed WUE values for the shelter experiment were not obtained from the full irrigation treatment (HHHH) but from the treatment that had deficit irrigation. For the same planting density treatments in the field experiment, WUE for the medium irrigation treatments were almost the same or even higher than for the full irrigation treatment, e.g., simulated WUE for the $PD_1 + W_M$ treatment was only 0.09% less than that for the $PD_1 + W_H$ treatment , while the observed WUE for the $PD_1 + W_M$ treatment was 48% higher than that for the $PD_1 + W_H$ treatment. The results indicated that deficit irrigation can enhance WUE effectively in a certain range.

Optimum Sowing Date

Predicted Grain Yield

An analysis to determine the optimum sowing date for winter wheat production on the Guanzhong Plain was conducted using the CSM–CERES–Wheat model. The simulated average yields were obtained on the basis of long-term historical daily weather data for the field experiment among all the scenarios and ranged from 4.1 to 11.3 t ha^{-1} depending on the different sowing dates (Fig. 5). For all the scenarios, the simulated yield had a similar trend for different planting dates, and there was an increase in the risk of obtaining low yields for the late sowing dates. When the sowing date was delayed from 27 August to 7 September, yield increased from 8.69 to 9.45 t ha^{-1} at an average rate of 76 kg ha^{-1} d^{-1}. However, delaying the sowing date from 7 September to 27 October caused a decrease in yield from 9.45 to 5.89 t ha^{-1} at a rate of 70 kg ha^{-1} d^{-1}. Generally, the highest yield was obtained for the 7 September sowing date,

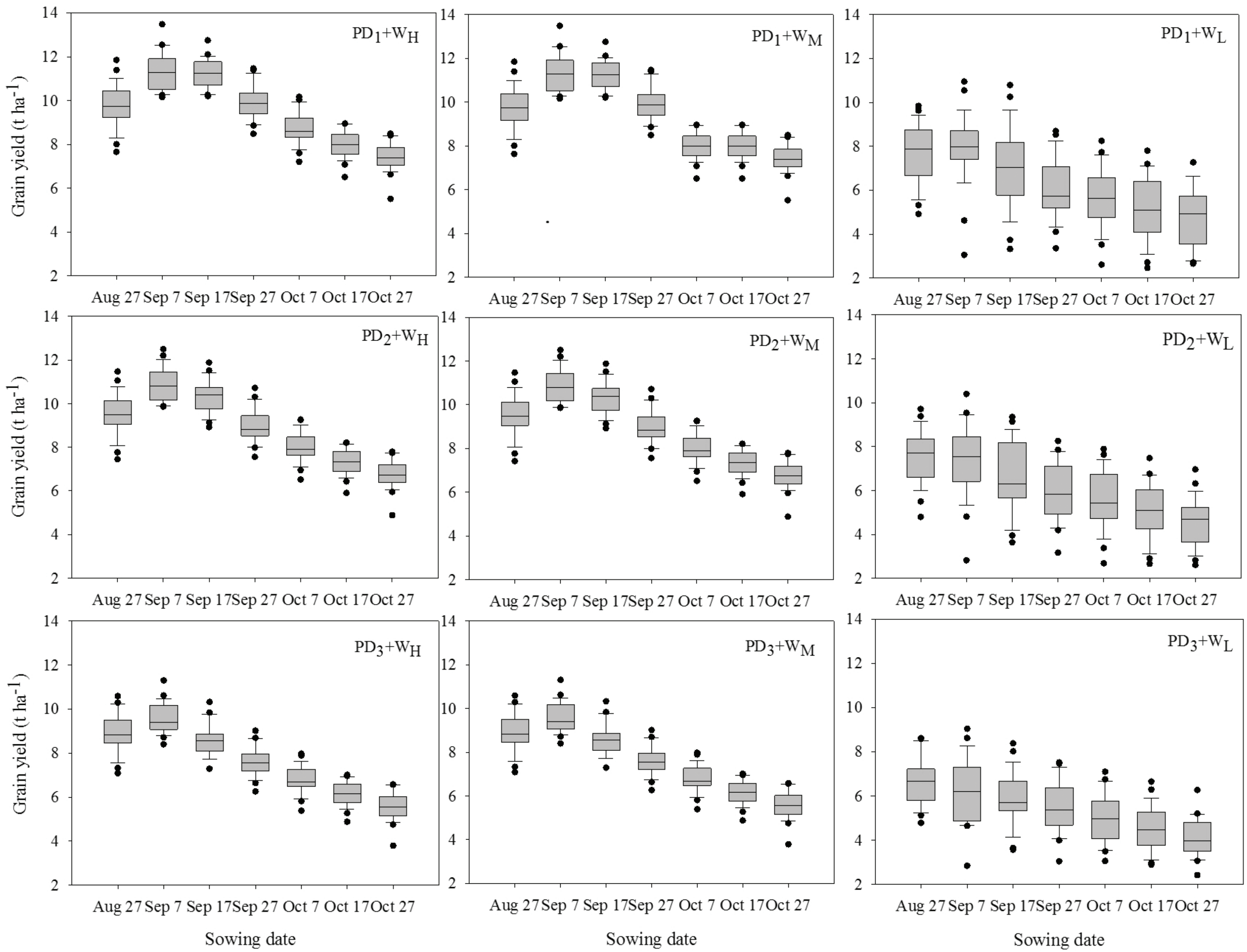

Fig. 5. Simulated yields as a function of planting date from 30-yr simulations (1984–2013) under different planting density (PD_1, PD_2, PD_3 for high, medium, and low planting density, respectively) and irrigation (W_H, W_M, and W_L for high, medium, and low irrigation amounts) scenarios with different sowing dates.

which was much earlier than the normal local sowing date, which ranges from 1 to 15 October. The lowest yield was found for the August planting dates, which could partially be caused by a high maximum temperature during the period, which ranged from 32.2 to 39.3°C during the early phase of crop growth. This resulted in an acceleration of crop development and a reduction in canopy cover and aboveground biomass production, which resulted in a reduction in yield components.

Simulated yield under the high and medium irrigation level scenarios did not show much difference, while the yield for the rainfed scenarios was much lower than for the two irrigation levels. For example, the median yield of the $PD_1 + W_L$, $PD_2 + W_L$, and $PD_3 + W_L$ scenarios for the 7 September sowing date was reduced by 30.0, 31.6, and 35.1%, respectively, compared with the $PD_1 + W_M$, $PD_2 + W_M$, and $PD_3 + W_M$ scenarios.

Predicted Irrigation Requirement

The average simulated irrigation amount was obtained on the basis of long-term historical daily weather data as well for the different scenarios with the varied planting dates. The automated irrigation was set when the soil water content dropped to a certain percentage of the field capacity. The simulated result showed that the irrigation amount increased gradually as the sowing date was delayed from 27 August, and the largest irrigation amount applied among all the scenarios was for 27 September with a rainfall of 221 mm (Table 8). From that day on, both the irrigation amount and rainfall began to decrease gradually. The irrigation amount for the high irrigation level scenarios was higher than the medium irrigation level scenarios. However, the yield for the medium irrigation scenarios was almost the same as the high level scenarios (Fig. 5), indicating that the medium irrigation level could meet the water demand for winter wheat production during the growing season. Zhang et al. (2010) analyzed the grain yield and WUE of different groups of winter wheat cultivars (26 in total) with different water deficit levels, and found that for better yield and WUE, winter wheat might not need full irrigation.

Predicted Water Use Efficiency and Irrigation Water Use Efficiency

Water use efficiency was defined as the simulated grain yield per unit of simulated ET, calculated from Eq. [1], and IWUE was estimated as the increased grain yield that was contributed by irrigation water applied, calculated from Eq. [2]. Both WUE and IWUE were high on sowing dates 7 and 17 September (Table 9). Our results showed that, when planted on those dates, winter wheat was able to produce more grain yield per unit of water applied than the other sowing dates. The grain yield and WUE on 7 September was higher than for 17 September (Fig. 5). The latter sowing date had a higher IWUE, showing that sowing

Table 8. Simulated irrigation amount based on long–term analysis for winter wheat planted on different dates and grown under different scenarios.

Scenario†	Irrigation amount						
	27 Aug.	7 Sept.	17 Sept.	27 Sept.	7 Oct.	17 Oct.	27 Oct.
	mm						
$PD_1 + W_H$	273.7	300.1	324.9	328.9	326.0	322.3	316.2
$PD_1 + W_M$	250.6	276.1	297.1	305.4	293.0	280.4	276.3
$PD_1 + W_L$	0	0	0	0	0	0	0
$PD_2 + W_H$	265.2	300.8	320.6	317.4	311.7	305.8	300.4
$PD_2 + W_M$	243.0	276.6	296.1	292.4	272.2	259.7	250.0
$PD_2 + W_L$	0	0	0	0	0	0	0
$PD_3 + W_H$	261.2	294.5	305.9	295.2	284.4	278.3	268.2
$PD_3 + W_M$	239.3	269.9	276.0	259.6	239.1	225.6	210.6
$PD_3 + W_L$	0	0	0	0	0	0	0

† PD_1, high planting density; PD_2, medium planting density; PD_3, low planting density; W_H, high irrigation amount; W_M, medium irrigation amount; W_L, low irrigation amount.

Table 9. Simulated water use efficiency (WUE) and irrigation water use efficiency (IWUE) based on long–term analysis for winter wheat planted on different dates and grown under different scenarios.

	27 Aug.		7 Sept.		17 Sept.		27 Sept.		7 Oct.		17 Oct.		27 Oct.	
Scenario†	WUE	IWUE	WUE	IWUE	WUE	IWUE	WUE	IWUE	WUE	IWUE	WUE	IWUE	WUE	IWUE
	$kg\ ha^{-1}\ m^{-1}$													
$PD_1 + W_H$	21.0	7.9	23.5	11.2	23.3	12.9	20.8	11.6	19.1	9.4	18.3	8.9	17.5	8.4
$PD_1 + W_M$	21.1	8.5	23.6	12.2	23.4	14.1	21.1	12.5	19.6	10.4	18.8	10.3	18.2	9.6
$PD_1 + W_L$	22.0	–	23.5	–	21.6	–	19.4	–	18.8	–	17.9	–	17.3	–
$PD_2 + W_H$	20.7	7.3	22.7	11.4	21.5	11.6	19.2	9.7	18.0	7.7	17.1	7.6	16.4	7.3
$PD_2 + W_M$	20.8	6.8	22.8	13.0	21.7	15.1	19.6	13.9	18.5	11.5	17.8	11.9	17.2	11.5
$PD_2 + W_L$	22.2	–	22.0	–	20.3	–	18.8	–	18.6	–	17.5	–	16.6	–
$PD_3 + W_H$	19.6	8.6	20.4	11.5	18.2	8.6	16.9	7.1	15.9	6.2	15.0	5.9	14.2	5.3
$PD_3 + W_M$	19.7	9.4	20.5	12.5	18.5	9.6	17.4	8.1	16.6	7.4	15.9	7.3	15.2	6.8
$PD_3 + W_L$	19.6	–	18.7	–	18.3	–	17.7	–	16.9	–	16.0	–	15.3	–

† PD_1, high planting density; PD_2, medium planting density; PD_3, low planting density; W_H, high irrigation amount; W_M, medium irrigation amount; W_L, low irrigation amount.

on 17 September would be a better use of irrigation water. The IWUE is superior for studying the efficiency in use of irrigation than WUE (Farré and Faci, 2009). For example, not all irrigation water is lost to ET. A fraction of the ETc comes from sources other than irrigation. The relationship between yield (Y) and irrigation water applied (I) is economically more important than the relationship between Y and ETc (Farré and Faci, 2009).

DISCUSSION

The CSM–CERES–Wheat model realistically simulated phenology, total aboveground biomass, and grain yield of winter wheat, with NRMSE values ranging from 0.8 to 15.4%. However, the model simulated in-season biomass and LAI less accurately, and the NRMSE ranged between 14.2% (∼65%) and 15.4% (∼36%), respectively. The simulation accuracy for winter wheat biomass varied for the different treatments that had different water deficits in each growth stage. In general, the model was inaccurate in simulating winter wheat biomass under stressed conditions. Taking the open field experiments as an example, under the same planting density, the NRMSE values increased as the irrigation amount decreased. And for the shelter experiment, the NRMSE for the treatments with severe water deficit during the jointing stage was larger than 30 and 40% for the 2011–2012 and 2012–2013 growing seasons, respectively. The result indicates that water stress has a significant influence on winter wheat biomass and grain yield. However, the model could not adequately describe the water stress sensitivity in the early growth stage and could not quantify the effects of water stress on seedling roots and leaf growth of winter wheat. DeJonge et al. (2012) found that enhancing the ET calculation accuracy is the basic way to improve the ability of the CERES model to simulate crop growth under water stress conditions. In addition, moderate water stress has a positive effect on the growth of winter wheat in the early stages, but severe water stress would restrain root growth, resulting in decreased root activity (Sun et al., 2004). Yao et al. (2015) suggested adding an additional water stress factor in the CERES model to describe the relationships between water stress and root growth in seedlings of winter wheat. Thus, the accuracy of the model to simulate crop growth under water stress in the early stages might be increased.

According to the seasonal analysis, the model simulated that the optimum sowing date was on 17 September for Xiaoyan 22 winter wheat at the experimental sites. The sowing date always affected wheat grain yield by changing the light and temperature conditions during the whole winter wheat growth period (Shan, 2001). In general, when the sowing date was too early, winter wheat grew rapidly due to the high temperatures and developed rapidly before winter. This resulted in frost damage and decreased the final grain yield. On the other hand, early sowing dates enhance the interception of solar radiance of a crop, allowing it to accumulate more dry matter (Stapper and Harris, 1989). However, if sowing was too late, winter wheat had insufficient tillers after winter and developed slowly in the early stage while growing rapidly in the late stage. This resulted in small spikes and less grain, leading to lower grain yield (Zhu et al., 2000). In general, spike numbers decreased as the sowing date was delayed within a critical range of sowing dates. However, grain numbers per spike always increased as sowing was delayed (Li et al., 2001). Liu et al. (2009) indicated that the planting density significantly influenced winter wheat growth and development, especially for tiller numbers and spike numbers, which impact grain yield. Thus, increasing planting density is the main method to get more spikes under late sowing conditions.

On the Guanzhong Plain, winter wheat is usually planted after summer maize (*Zea mays* L.) and the sowing date for winter wheat is highly dependent on the harvest date of summer maize, which normally occurs in late September or early October. However, the optimum sowing date from our model simulations was almost 20 to 30 d earlier than the normal local sowing date, and the predicted yield was very high even in rainfed scenarios (Fig. 5). The reason might be that the model could not simulate the impact of wintering time on the cultivar Xiaoyan 22 accurately. Actually, the frost risk in later winter for Xiaoyan 22 was very high and the model did not consider this part properly. Therefore, combining the model simulations and local management, we determined that the optimum sowing date for Xiaoyan 22 at the experiment site is 7 October, which is 20 d later than our simulated result.

CONCLUSIONS

Our analysis demonstrated that the performance of the CSM–CERES–Wheat model was good, as indicated by the correspondence of the simulated crop phenology, biomass partitioning, total aboveground biomass, LAI, and grain yield with the observed data. The simulations using the calibrated cultivar coefficients for Xiaoyan 22 with independent data resulted in accurate predictions of crop phenology, growth, and development. However, some simulated values related to in-season parameters (i.e., leaf biomass, stem biomass, and LAI) showed relatively high normalized RMSE values (>30%), and this needs to be improved.

In addition, based on the results of the 2 yr of field experiments, the medium irrigation level with high planting density was found to be the best management practice. Taking the constraints of local management conditions and cultivar characteristics into account, the CSM–CERES–Wheat model may not be a suitable tool for optimizing the planting date on the Guanzhong Plain.

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REFERENCES

Alexandrov, V.A., and G. Hoogenboom. 2000. Vulnerability and adaptation assessments of agricultural crops under climate change in the southeastern USA. Theor. Appl. Climatol. 67:45–63. doi:10.1007/s007040070015

Anothai, J., C.M.T. Soler, A. Green, T.J. Trout, and G. Hoogenboom. 2013. Evaluation of two evapotranspiration approaches simulated with the CSM–CERES–Maize model under different irrigation strategies and the impact on maize growth, development and soil moisture content for semi-arid conditions. Agric. For. Meteorol. 176:64–76. doi:10.1016/j.agrformet.2013.03.001

Arora, V.K., H. Singh, and B. Singh. 2007. Analyzing wheat productivity responses to climatic, irrigation and fertilizer-nitrogen regimes in a semi-arid sub-tropical environment using the CERES–Wheat model. Agric. Water Manage. 94:22–30. doi:10.1016/j.agwat.2007.07.002

Blum, A. 2009. Effective use of water (EUW) and not water-use efficiency (WUE) is the target of crop yield improvement under drought stress. Field Crops Res. 112:119–123. doi:10.1016/j.fcr.2009.03.009

Boote, K.J., J.W. Jones, and N.B. Pickering. 1996. Potential uses and limitations of crop models. Agron. J. 88:704–716. doi:10.2134/agronj1996.00021962008800050005x

Debaeke, P., and A. Aboudrare. 2004. Adaptation of crop management to water-limited environments. Eur. J. Agron. 21:433–446. doi:10.1016/j.eja.2004.07.006

DeJonge, K., J. Ascough, and A. Andales. 2012. Improving evapotranspiration simulations in the CERES–Wheat model under limited irrigation. Agric. Water Manage. 115:92–103. doi:10.1016/j.agwat.2012.08.013

Dettori, M., C. Cesaraccio, A. Motroni, D. Spano, and P. Duce. 2011. Using CERES–Wheat to simulate durum wheat production and phenology in southern Sardinia, Italy. Field Crops Res. 120:179–188. doi:10.1016/j.fcr.2010.09.008

Eck, H.V. 1986. Effects of water deficits on yield, yield components, and water use efficiency of irrigated corn. Agron. J. 78:1035–1040. doi:10.2134/agronj1986.00021962007800060020x

Ehdaie, B. 1995. Variation in water-use efficiency and its components in wheat: II. Plot and field experiments. Crop Sci. 35:1617–1626. doi:10.2135/cropsci1995.0011183X003500060017x

Farré, I., and J.M. Faci. 2009. Deficit irrigation in maize for reducing agricultural water use in a Mediterranean environment. Agric. Water Manage. 96:383–394. doi:10.1016/j.agwat.2008.07.002

Garrison, M.V., W.D. Batchelor, R.S. Kanwar, and J.T. Ritchie. 1999. Evaluation of the CERES–Maize water and nitrogen balances under tile-drained conditions. Agric. Syst. 62:189–200. doi:10.1016/S0308-521X(99)00064-5

Geerts, S., and D. Raes. 2009. Deficit irrigation as an on-farm strategy to maximize crop water productivity in dry areas. Agric. Water Manage. 96:1275–1284. doi:10.1016/j.agwat.2009.04.009

Guerra, L.C., A. Garcia y Garcia, J.E. Hook, K.A. Harrison, D.L. Thomas, D.E. Stooksbury, and G. Hoogenboom. 2007. Irrigation water use estimates based on crop simulation models and kriging. Agric. Water Manage. 89:199–207. doi:10.1016/j.agwat.2007.01.010

He, J., H. Cai, and J. Bai. 2013. Irrigation scheduling based on CERES–Wheat model for spring wheat production in the Minqin Oasis in Northwest China. Agric. Water Manage. 128:19–31. doi:10.1016/j.agwat.2013.06.010

Heinemann, A.B., G. Hoogenboom, and R.T. de Faria. 2002. Determination of spatial water requirements at county and regional levels using crop models and GIS: An example of the state of Parana, Brazil. Agric. Water Manage. 52:177–196. doi:10.1016/S0378-3774(01)00137-8

Heng, L.K., S. Asseng, K. Mejahed, and M. Rusan. 2007. Optimizing wheat productivity in two rain-fed environments of the West Asia–North Africa region using a simulation model. Eur. J. Agron. 26:121–129. doi:10.1016/j.eja.2006.09.001

Hoogenboom, G. 2000. Contribution of agrometeorology to the simulation of crop production and its applications. Agric. For. Meteorol. 103:137–157. doi:10.1016/S0168-1923(00)00108-8

Hoogenboom, G., J.W. Jones, P. Winkens, C. Porter, K.J. Boote, L.A. Hunt, et al. 2010. Decision Support System for Agrotechnology Transfer, Version 4.0. Univ. of Hawaii, Honolulu.

Hoogenboom, G., J.W. Jones, P.W. Winkens, C.H. Porter, K.J. Boote, L.A. Hunt, et al. 2011. Decision Support System for Agrotechnology Transfer, Version 4.5. Univ. of Hawaii, Honolulu.

Hu, Y., Y. Yang, Y. Yang, and Y. Wang. 2009. Effect of irrigation on winter wheat yield, evapotranspiration and water use efficiency in North China Plain. (In Chinese with English abstract.) Eng. J. Wuhan Univ. 42:1–5.

Huang, S., B. Hou, J. Chang, Q. Huang, and Y. Chen. 2014. Copulas-based probabilistic characterization of the combination of dry and wet conditions in the Guanzhong Plain, China. J. Hydrol. 519:3204–3213. doi:10.1016/j.jhydrol.2014.10.039

Hundal, S.S., and P. Kaur. 1997. Application of the CERES–Wheat model to yield predictions in the irrigated plains of the Indian Punjab. J. Agric. Sci. 129:13–18. doi:10.1017/S0021859697004462

Hunt, L.A., and K.J. Boote. 1998. Data for model operation, calibration and evaluation. In: G.Y. Tsuji et al, editors, Understanding options for agricultural production. Kluwer Acad., Dordrecht, the Netherlands. p. 9–39. doi:10.1007/978-94-017-3624-4_2

Iqbal, M.A., Y. Shen, R. Stricevic, H. Pei, H. Sun, E. Amiri, et al. 2014. Evaluation of the FAO AquaCrop model for winter wheat on the North China Plain under deficit irrigation from field experiment to regional yield simulation. Agric. Water Manage. 135:61–72. doi:10.1016/j.agwat.2013.12.012

Jamieson, P.D., J.R. Porter, and D.R. Wilson. 1991. A test of computer simulation model ARCWHEAT1 on wheat crops grown in New Zealand. Field Crops Res. 27:337–350. doi:10.1016/0378-4290(91)90040-3

Ji, J., H. Cai, J. He, and H. Wang. 2014. Performance evaluation of CERES–Wheat model in Guanzhong Plain of Northwest China. Agric. Water Manage. 144:1–10. doi:10.1016/j.agwat.2014.04.016

Jones, J.W., G. Hoogenboom, C.H. Porter, K.J. Boote, W.D. Batchelor, L.A. Hunt, et al. 2003. The DSSAT cropping system model. Eur. J. Agron. 18:235–265. doi:10.1016/S1161-0301(02)00107-7

Jones, J.W., G. Hoogenboom, P.W. Wilkens, C.H. Porter, and G.Y. Tsuji. 2010. Decision Support System for Agrotechnology Transfer, Version 4.5. DSSAT v4.5. ICASA Tools. Univ. of Hawaii, Honolulu.

Jones, P., and P. Thornton. 2003. The potential impacts of climate change on maize production in Africa and Latin America in 2055. Global Environ. Change 13:51–59. doi:10.1016/S0959-3780(02)00090-0

Lamb, M., R. Sorensen, R.C. Nuti, C.L. Butts, W.H. Faircloth, D. Eigenberg, and D.L. Rowland. 2011. Agronomic and economic effect of irrigation rate in corn produced in Georgia. Crop Manage. 10(1). doi:10.1094/CM-2011-0721-02-RS

Langensiepen, M., H. Hanus, P. Schoop, and W. Gräsle. 2008. Validating CERES–Wheat under north-German environmental conditions. Agric. Syst. 97:34–47. doi:10.1016/j.agsy.2007.11.001

Li, C., W. Cao, and Y. Zhang. 2001. Floret position differences in seed setting characteristic of different sowing dates and varieties. (In Chinese with English abstract.) Acta Agric. Boreali-Sinica 16:1–7.

Liu, J., D. Wiberg, A.J.B. Zehnder, and H. Yang. 2007. Modeling the role of irrigation in winter wheat yield, crop water productivity, and production in China. Irrig. Sci. 26:21–33. doi:10.1007/s00271-007-0069-9

Liu, W., X. Chen, J. Yin, and P. Du. 2009. Effects of sowing date and planting density on population trait and grain yield of winter wheat cultivar Yumai 49-198. (In Chinese with English abstract.) J. Triticeae Crops 29:464–469.

Mall, R.K., M. Lal, V.S. Bhatia, L.S. Rathore, and R. Singh. 2004. Mitigating climate change impact on soybean productivity in India: A simulation study. Agric. For. Meteorol. 121:113–125. doi:10.1016/S0168-1923(03)00157-6

Mavromatis, T., K.J. Boote, J.W. Jones, A. Irmak, D. Shinde, and G. Hoogenboom. 2001. Developing genetic coefficients for crop simulation models with data from crop performance trials. Crop Sci. 41:40–51. doi:10.2135/cropsci2001.41140x

Nijbroek, R., G. Hoogenboom, and J.W. Jones. 2003. Optimizing irrigation management for a spatially variable soybean field. Agric. Syst. 76:359–377. doi:10.1016/S0308-521X(02)00127-0

Pecetti, L., and P.A. Hollington. 1997. Application of the CERES–Wheat simulation model to durum wheat in two diverse Mediterranean environments. Eur. J. Agron. 6:125–139. doi:10.1016/S1161-0301(96)02039-4

Pereira, L.S., P. Paredes, E.D. Cholpankulov, O.P. Inchenkova, P.R. Teodoro, and M.G. Horst. 2009. Irrigation scheduling strategies for cotton to cope with water scarcity in the Fergana Valley, central Asia. Agric. Water Manage. 96:723–735. doi:10.1016/j.agwat.2008.10.013

Ritchie, J.T., U. Singh, D. Godwin, and W.T. Bowen. 1998. Cereal growth, development and yield. In: G.Y. Tsuji et al., editors, Understanding options for agricultural production. Kluwer Acad., Dordrecht, the Netherlands. p. 79–98. doi:10.1007/978-94-017-3624-4_5

Ruíz-Nogueira, B., K.J. Boote, and F. Sau. 2001. Calibration and use of CROPGRO–Soybean model for improving soybean management under rainfed conditions. Agric. Syst. 68:151–173. doi:10.1016/S0308-521X(01)00008-7

Salazar, M.R., J.E. Hook, A. Garcia y Garcia, J.O. Paz, B. Chaves, and G. Hoogenboom. 2012. Estimating irrigation water use for maize in the southeastern USA: A modeling approach. Agric. Water Manage. 107:104–111. doi:10.1016/j.agwat.2012.01.015

Savin, R., E.H. Satorre, A.J. Hall, and G.A. Slafer. 1995. Assessing strategies for wheat cropping in the monsoonal climate of the Pampas using the CERES–Wheat simulation model. Field Crops Res. 42:81–91. doi:10.1016/0378-4290(95)00029-P

Shan, Y. 2001. Wheat yield cultivation techniques principle. (In Chinese.) Beijing Sci. Technol. Press, Beijing.

Sinclair, T.R., and N.G. Seligman. 1996. Crop modeling: From infancy to maturity. Agron. J. 88:698–704. doi:10.2134/agronj1996.00021962008800050004x

Soler, C.M.T., P.C. Sentelhas, and G. Hoogenboom. 2007. Application of the CSM–CERES–Maize model for planting date evaluation and yield forecasting for maize grown off-season in a subtropical environment. Eur. J. Agron. 27:165–177. doi:10.1016/j.eja.2007.03.002

Stapper, M., and H.C. Harris. 1989. Assessing the productivity of wheat genotypes in a Mediterranean climate, using a crop simulation model. Field Crops Res. 20:129–152. doi:10.1016/0378-4290(89)90057-9

Sun, C., S. Bai, and B. Bai. 2004. Effect of water stress on root growth and physiological characters of wheat seedlings. (In Chinese with English abstract.) J. Jilin Agric. Univ. 25:485–489.

Sun, H.-Y., C.-M. Liu, X.-Y. Zhang, Y.-J. Shen, and Y.-Q. Zhang. 2006. Effects of irrigation on water balance, yield and WUE of winter wheat in the North China Plain. Agric. Water Manage. 85:211–218. doi:10.1016/j.agwat.2006.04.008

Tang, J., H. Folmer, and J. Xue. 2013. Estimation of awareness and perception of water scarcity among farmers in the Guanzhong Plain, China, by means of a structural equation model. J. Environ. Manage. 126:55–62. doi:10.1016/j.jenvman.2013.03.051

Thornton, P.K., G. Hoogenboom, P.W. Wilkens, and W.T. Bowen. 1995. A computer program to analyze multiple-season crop model outputs. Agron. J. 87:131–136.

Thornton, P.K., G. Hoogenboom, P.W. Wilkens, and J.W. Jones. 1998. Seasonal analysis. In: G.Y. Tsuji et al., editors, DSSAT version 3. Vol. 3-2. Univ. of Hawaii, Honolulu. p. 1–65.

Timsina, J., D. Godwin, E. Humphreys, Yadvinder-Singh, Bijay-Singh, S.S. Kukal, and D. Smith. 2008. Evaluation of options for increasing yield and water productivity of wheat in Punjab, India using the DSSAT–CSM–CERES–Wheat model. Agric. Water Manage. 95:1099–1110. doi:10.1016/j.agwat.2008.04.009

Timsina, J., and E. Humphreys. 2006. Performance of CERES–Rice and CERES–Wheat models in rice–wheat systems: A review. Agric. Syst. 90:5–31. doi:10.1016/j.agsy.2005.11.007

Wang, X., Q. Wang, J. Fan, and Q. Fu. 2013. Evaluation of the AquaCrop model for simulating the impact of water deficits and different irrigation regimes on the biomass and yield of winter wheat grown on China's Loess Plateau. Agric. Water Manage. 129:95–104. doi:10.1016/j.agwat.2013.07.010

Xiong, W., D. Conway, I. Holman, and E. Lin. 2008. Evaluation of CERES–Wheat simulation of wheat production in China. Agron. J. 100:1720–1728. doi:10.2134/agronj2008.0081

Yang, J.M., J.Y. Yang, S. Liu, and G. Hoogenboom. 2014. An evaluation of the statistical methods for testing the performance of crop models with observed data. Agric. Syst. 127:81–89. doi:10.1016/j.agsy.2014.01.008

Yang, Y., M. Watanabe, X. Zhang, J. Zhang, Q. Wang, and S. Hayashi. 2006. Optimizing irrigation management for wheat to reduce groundwater depletion in the piedmont region of the Taihang Mountains in the North China Plains. Agric. Water Manage. 82:25–44. doi:10.1016/j.agwat.2005.07.020

Yao, N., Y. Zhou, L. Song, J. Liu, Y. Li, S. Wu, et al. 2015. Parameter estimation and verification of DSSAT–CERES–Wheat model for simulation of growth and development of winter wheat under water stresses at different growth stages. (In Chinese with English abstract.) Trans. Chin. Soc. Agric. Eng. 31:138–150.

Zhang, B., F.-M. Li, G. Huang, Z.-Y. Cheng, and Y. Zhang. 2006. Yield performance of spring wheat improved by regulated deficit irrigation in an arid area. Agric. Water Manage. 79:28–42. doi:10.1016/j.agwat.2005.02.007

Zhang, X., S. Chen, H. Sun, Y. Wang, and L. Shao. 2010. Water use efficiency and associated traits in winter wheat cultivars in the North China Plain. Agric. Water Manage. 97:1117–1125. doi:10.1016/j.agwat.2009.06.003

Zhu, F., J. Wu, and Z. Yu. 2000. Effect of sowing density on Yumai 29 group individual quality traits. (In Chinese with English abstract.) Jiangsu Agric. Sci. 5:21–24.