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Research article

The applicability evaluation and drought validation of the WOFOST model for the simulation of winter wheat growth in Shandong Province, China

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ABSTRACT

The yield of winter wheat in Shandong Province is of great significance for ensuring regional and national food security. To reduce the risk of production loss, the WOFOST model was used to simulate the winter wheat growth to obtain the quantitative and dynamic information. Based on the observational data, a moisture control experiment and the trial and error method, the applicability and drought simulation of the WOFOST model were evaluated for winter wheat growth. For the simulation of the seedling period, flowering period, and maturity period of winter wheat in Shandong Province, the R^2 were 0.95, 0.69, and 0.68 respectively. The D-index were 0.99, 0.89, and 0.86 respectively. The mean absolute error (mAE) were 1.3, 4.3, and 4.1 respectively. And the nRMSE were 0.65%, 4.3%, and 3.2%, respectively. For the yield simulation, the R^2, D-index, mean relative error (mRE), and nRMSE were 0.48, 0.82, 10.5% and 12.8%, respectively. For the yield simulation under drought stress, the R^2, D-index, mRE, and nRMSE were 0.77, 0.93, 7.1%, and 7.4%, respectively. An evaluation index system was built through four different degrees of drought treatment between the jointing period and the flowering period. With the aggravation of drought, the growth indicators about the total above ground production (TAGP), maximum leaf area index (MAXLAI), total dry weight of leaves (TWLV), and total dry weight of stems (TWST) decreasing by 13.6–41.0%, 37.8–56.5%, 19.4–42.1%, and 20.3–51.2%, respectively. The results showed that this model could adequately simulate the formation process of yield under both normal and drought conditions.

1. Introduction

Meteorological factors are the most important external conditions affecting the growth of winter wheat (Wang et al., 2013; Liu et al., 2018). Climate change is causing extreme climate events to occur more frequently (IPCC, 2013). And meteorological factors have become the most important risk factors for winter wheat production, directly affecting yield formation and the input proportion of agricultural resource (Lv et al., 2013; Qu et al., 2019; Kothari et al., 2019). Research has shown that warming between the seedling period and heading period had a positive effect on the yield of winter wheat in Shandong Province, while warming between the heading period and grains filling period mainly had a negative effect (Xiao et al., 2014). And the insufficient precipitation in the key periods leads to an increase in yield fluctuation (Sun et al., 2017; Liu et al., 2020). The jointing stage of winter wheat is an important period for the differentiation of tiller and panicle (Cui et al., 2019; Zhang et al., 2019). At this period, dry matter accumulation entered a stage of rapid growth, and any degree of drought would cause the decrease of dry matter (Yan et al., 2011). And the yield of winter wheat would decrease significantly under severe drought conditions of jointing period (Jin et al., 2019). Meanwhile, it's a frequent period of spring drought in Shandong wheat area as the little precipitation and

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large evaporation. In particular, the occurrence frequency and hazard of spring drought were gradually strengthened with the aggravation of climate warming (Yuan et al., 2015).

If the quantitative growth information could be obtained in real-time, the impacts of changes in meteorological factors could be evaluated on the growth and development of winter wheat. And the effective countermeasures could be put forward timely. For this purpose, there are two mainly methods. The one is the observational experiments. Observational experiments can obtain a large number of important data to test hypotheses or evaluate causal relationships. However, the experiments require long-term observation of multiple treatments. Their processes are time-consuming and energy-consuming. Since this method has certain difficulty and great limitation in implementation. Another method is the simulation of crop mechanism models. This method is more quantitative and efficient. Crop mechanism models can simulate the growth and yield formation of crops under different climate and weather patterns (Liu et al., 2006; Osborne et al., 2010; Guo, 2015). And they can greatly expand the temporal and spatial scale of impact assessment.

Winter wheat (Triticum aestivum L.) has the largest planting area of any grain crop in China (Hou et al., 2019). Shandong Province is one of the most important production areas for winter wheat. The planting area and total yield of winter wheat in this province account for 17.8% and 19.8% of China's total, respectively (National Bureau of Statistics, 2019). Its yield is of great significance to guarantee the food security of the region and even the whole country (Ren et al., 2019). For the growth monitoring and diagnostic evaluation of winter wheat, crop mechanism models can provide a dynamic and efficient method.

Among crop models, the WOFOST model is a widely used mechanism model as its open-source code and relatively simple parameter adjustment (Confalonieri, 2010; Wang et al., 2015; Dong et al., 2019; Ceglar et al., 2019). It is a dynamic explanatory model developed by Wageningen University in the Netherlands and the World Food Research Center to simulate crop growth under specific soil and climate conditions (Van Diepen et al., 1989; De Wit et al., 2019). By using a daily time step, the model can simulate crop growth dynamically and quantitatively at the potential level, water limit level, and nutrient limit level, respectively (Yang et al., 2013). The WOFOST model can be used to describe the growth and development process of different crops in different regions by changing the parameters (Xie et al., 2006; Chen et al., 2007; Bregaglio et al., 2015; Castañeda-Vera et al., 2015). And it has been applied to different crops in many regions of China (Ma et al., 2005; Luan et al., 2014; Sun et al., 2016; Gao et al., 2006). However, there are relatively few simulation studies on the growth and yield formation of winter wheat in Shandong province by this model, especially for the validation of drought stress in the key period. As a result, the growth and yield of winter wheat cannot be dynamically and quantitatively monitored and estimated in this province.

Based on this, the present study conducts the verification of the WOFOST model for winter wheat in Shandong Province by the observational data, field test results and the trial and error method. And its applicability for the simulation of drought process is evaluated by the moisture control test of the key period of winter wheat. This study would provide a method to objectively evaluate the influence of meteorological factors fluctuation on winter wheat growth and yield formation. And this study would provide references for the drought validation, promoted application of WOFOST model, and drought impact assessment.

2. Materials and methods

2.1. Study area and data type

Shandong province is located between 34° 22.9 ' ~ 38° 24.01 ′ N and 114° 47.5 ' ~ 122° 42.3 ′ E in the east coast of China (Figure 1). It borders Hebei, Henan, Anhui and Jiangsu provinces from north to south. Shandong is 721.03 km long from east to west and 437.28 km long from north to south. The land area of the province is 155,800 square kilometers.

The model-driven data used in this study include daily weather data and soil parameter data. The weather data were obtained from automatic weather stations in Shandong Province, including solar radiation, minimum temperature, maximum temperature, early morning vapor pressure, average wind speed (height: 2 m) and precipitation (Table 1). The soil parameter data comprised the soil water holding capacity, soil water conductivity, soil bulk density, field water holding capacity, wilting coefficient and saturated soil water content, and were obtained from soil water observation stations in Shandong Province (Table 1).

The data regarding winter wheat variety, growth period, and yield structure were obtained from 16 agrometeorological observation stations in Shandong Province (Table 1)—one each in Laiyang, Wendeng, Fushan, Laizhou, Jiaozhou, Weifang, Zibo, Taian, Juxian, Linyi, Jining, Heze, Caoxian, Huimin, Dezhou, and Liaocheng (Figure 1)—between 2010 and 2015. The seedling period of winter wheat is generally in October in Shandong Province. Its flowering period is generally in late April to early May. And its maturity period is generally in June. Figure 2 shows the average temperature and precipitation of the growth period of winter wheat (from October of last year to June) in each agrometeorological observation stations. According to the geographical distribution of agrometeorological observation stations, main varieties of winter wheat and geographical zoning characteristics of Shandong Province, the parameter optimization regions were divided into five regions to improve the simulation accuracy, namely the northwest region, the central region, the southwest region, the southeast region, and the Jiaodong Peninsula region (Figure 1).

2.2. Design of moisture control test

The data of the drought simulation were from a moisture control experiment performed between October 2018 and June 2019 at the Taian Agrometeorological Experimental Station in Shandong Province (35.97° N, 117.26° E). The annual highest, lowest, and average temperature of the experimental station are 33.9, 6.4, and 15.1 °C, respectively. And the annual sunshine hours are 2200 h. The tested winter wheat variety was *Jimai 22.* It's the main cultivar in the northern winter wheat area. The test was carried out with a movable canopy for moisture control. The area of each test plot was 4 m × 4 m. Anti-seepage treatment was adopted at the bottom and periphery of the plots to ensure that each test plot was not affected by others. The soil of the test plots was sandy loam. Nitrogen, phosphorus, and potash fertilizers were applied before sowing. Phosphorus and potash fertilizer were used as base fertilizer, while nitrogen fertilizer was divided into base fertilizer and jointing fertilizer to ensure the supply of soil nutrients. The row spacing of winter wheat was 25 cm and the planting density was 2.5×10^6 basic seedlings per hm^2.

Four drought levels were designed in the test plots, and the winter wheat in the field with normal irrigation management level was taken as contrast (CK). A single-factor random block group design was adopted with three repetitions. Proper irrigation and moisture control were carried out 10 days before the jointing period of winter wheat. The relative soil humidity (the ratio of soil moisture content to field water holding capacity) in the test plots was controlled at about 60%. In the jointing period of winter wheat (02 April), each treatment was replenished with water at different amounts. The amount of water replenished was set according to the average annual precipitation (30.00 mm) and irrigation amount (45.00 mm) in April in Shandong Province (Table 2). In treatments T1, T2, T3, and T4, the amount of water reduction was 20%, 50%, 75%, and 100%, respectively. The layout of test plots was shown in Figure 3. The plots were rehydrated to the same degree as CK when the winter wheat entered the flowering period (26 April). The observed indexes were the soil moisture content (obtained via the drying and weighing method) and yield structure (spikelet number, infertile spikelet number, spike grain number, and thousand kernel weight).

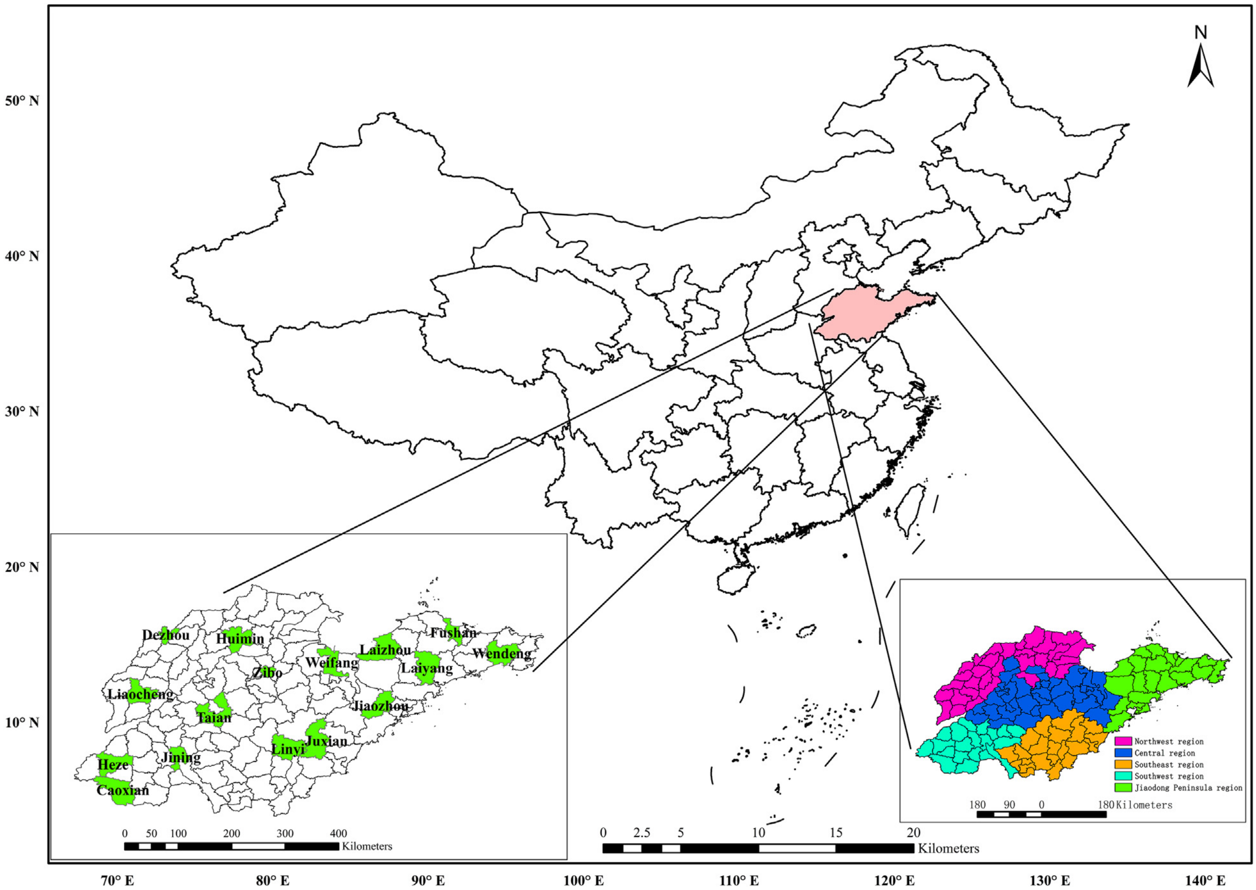

Figure 1. The study area, the 16 agrometeorological observation stations distribution and five parameter optimization regions.

2.3. Sensitive parameters of WOFOST model

The WOFOST model has a large number of parameters. To improve the working efficiency, it is necessary to carry out a sensitivity analysis of the model parameters (Wu et al., 2009; Gilardelli et al., 2018; Xing et al., 2020). Using an extended Fourier amplitude sensitivity testing (EFAST) (Jiang et al., 2011; Xing et al., 2017; He et al., 2016), the sensitivity parameters of the WOFOST model have been clarified, including seven parameters that are sensitive to the physical growth of crops (Table 3), 11 parameters that are sensitive to the potential yield (Table 4), and four parameters that are sensitive to the water limit yield (Table 5) (Huang et al., 2017; He et al., 2016).

In this research, the relevant accumulated temperature parameters were calculated based on the observed values from each observation station from 2010 to 2015. The dry matter distribution coefficients of stems, leaves, and organs, as well as other sensitive parameters, were measured by the test or calibrated using the trial and error method. For the validation of the growth period, the model was driven by the actual sowing period, and the starting dates of the subsequent growth period were simulated, including the seedling period, flowering period, and

Table 1. The data type.

Data name	Data content	Spatial resolution	Temporal resolution	Data Sources
Weather data	Solar radiation ($W{\cdot}m^{-2}$)	122 observation stations	2010–2015	Automatic weather stations
	Minimum temperature (°C)			
	Maximum temperature (°C)			
	Early morning vapor pressure (hPa)			
	Average wind speed (height: 2 m) ($m{\cdot}s^{-1}$)			
	Precipitation (mm)			
Soil parameter data	Soil water holding capacity (%)	231 observation stations	2010–2015	Soil water observation stations
	Soil water conductivity ($mm{\cdot}s^{-1}$)			
	Soil bulk density ($g{\cdot}cm^{-3}$)			
	Field water holding capacity (%)			
	Wilting coefficient (%)			
	Saturated soil water content (%)			
Agrometeorological observation data	Variety	16 observation stations	2010–2015	Agrometeorological observation stations
	Growth period			
	Yield structure			

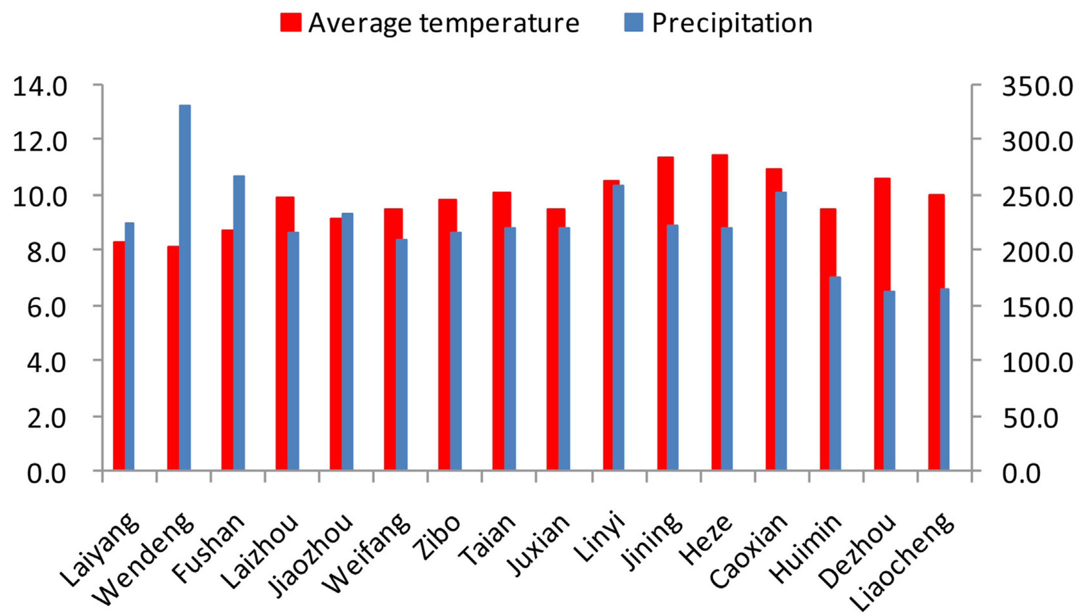

Figure 2. The average temperature and precipitation of the growing period of winter wheat (from October of last year to June) in 16 agrometeorological observation stations.

Table 2. The irrigation amounts of the moisture control treatments used in the field experiment.

Treatment	From jointing period to flowering period (from 02 Apr to 26 Apr)			
	T1	T2	T3	T4
Irrigation amount (mm)	60.00	37.50	18.75	0

maturity period. Considering agricultural meteorological conditions comprehensively, 2012 is a normal year. So 2012 was used as the parameters adjustment year, and 2010, 2011, 2013, 2014 and 2015 were used as validation years.

2.4. Indexes of parameter optimization

The coefficient of determination (R^2), Willmott consistency index (D-index), relative error (RE), normalized root-mean-square error (nRMSE), and absolute error (AE) were selected as the evaluation indexes for the model parameter optimization. R^2 reflects the consistency between the simulated value and the observed value. The value closer to 1 mean that the consistency and simulation effect of the model is better. The calculation formulae of the other indexes are as formula (1) to (4):

(1) D-index

$$D = 1 - \frac{\sum (SIM_i - OBS_i)^2}{\sum (|SIM_i - mOBS| + |OBS_i - mOBS|)^2} \tag{1}$$

where D, SIM, OBS, mOBS, and i represent the D-index, the model-simulated value, the observed value, the average value of the observed value, and the sample sequence, respectively. The same applies for Eqs. (2), (3), and (4) below. The value ranges from 0–1. And the larger value mean that the higher consistency.

(2) RE

$$RE = \frac{SIM_i - OBS_i}{OBS_i} * 100\% \tag{2}$$

where RE represents relative error. If the value of RE is less than 15%, the simulation result is acceptable. The smaller value mean that the better simulation result. And the same applies for Eqs. (3) and (4) below.

(3) nRMSE

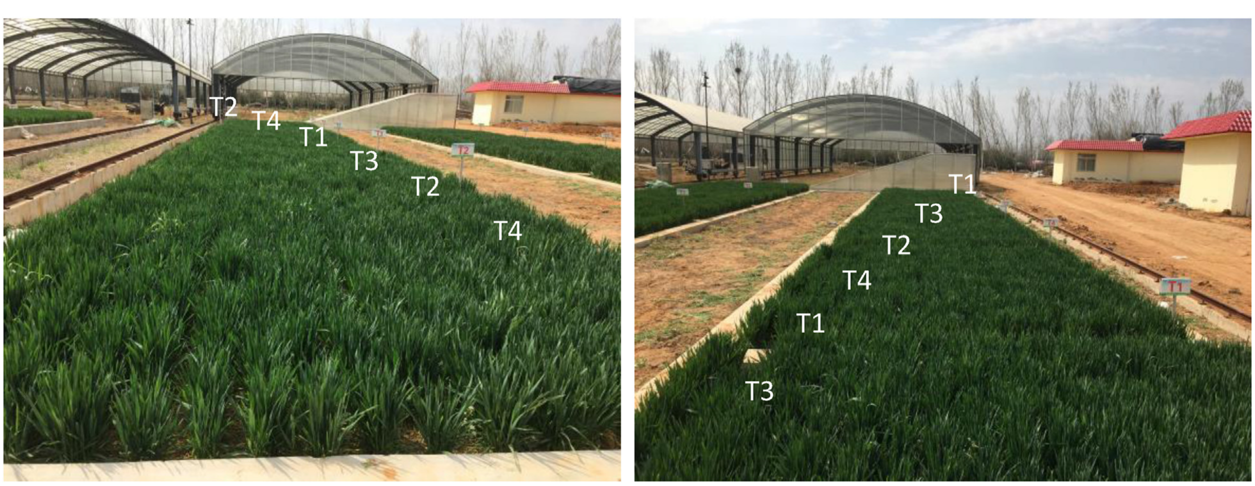

Figure 3. The layout photo of test plots.

Table 3. The parameters of crop physiological growth.

Parameters	Biological significances	Minimum value	Maximum value
TSUMEM	Thermal time from sowing to emergence (°C·d)	0	170
TSUM1	Thermal time from emergence to anthesis (°C·d)	150	1800
TUSM2	Thermal time from anthesis to maturity (°C·d)	400	1550
TBASEM	Lower threshold temperature for emergence (°C)	-10	8
DLO	Optimum day length (hr)	6	18
DLC	Critical day length (hr)	6	18
TEFFMX	Maximum effective temperature for emergence (°C)	18	32

$$nRMSE = \frac{\sqrt{\sum_{i=1}^{n}(OBS_i - SIM_i)^2 / n}}{\sum_{i=1}^{n} OBS_i / n} \times 100\% \quad (3)$$

where nRMSE and n represent the normalized root-mean-square error and the sample size respectively. If the value is less than 30%, the simulation result is acceptable.

(4) AE

$$AE = SIM_i - OBS_i \quad (4)$$

where AE represents absolute error. If the value about the growth period is less than 5 days, the simulation result is acceptable.

2.5. Assessment index of drought impact by WOFOST model

Completed the optimization of parameters, the reduction ranges (RR) of simulation results of WOFOST model are used to assess the impacts of drought. Its formula is shown as follows:

$$RR = \frac{SIM_d - SIM_p}{SIM_p} * 100\% \quad (5)$$

where RR, SIM_d and SIM_p represent the reduction ranges, the model-simulated value under drought treatments and potential growth conditions, respectively.

3. Results

3.1. Growth periods simulation

On the basis of the results of formula (1), 3 and (4), Figures 4, 5, and 6 show the comparison result for the observed value and simulated value of the seedling period, flowering period, and maturity period of winter wheat, respectively. For the seedling period, the R^2, D-index, mAE, and nRMSE were 0.95, 0.99, 1.3 and 0.65%, respectively (Figure 4). The flowering period is the dividing line between the vegetative growth and reproductive growth. The accurate simulation of the flowering period can guarantee the accurate simulation of yield formation. For the flowering period, the R^2, D-index, mAE, and nRMSE were 0.69, 0.89, 4.3 and 4.3%, respectively (Figure 5). For the maturity period, the R^2, D-index, mAE, and nRMSE were 0.68, 0.86, 4.1 and 3.2%, respectively (Figure 6).

Based on the results of formula (3) and (4), Table 6 show the evaluation indexes of the simulated values for each observation station for the seedling period, flowering period, and maturity period, respectively. For the seedling period, the R^2 of most observation stations ranged from 0.77–0.99. The mAE ranged from 1–2 days. And the nRMSE ranged from 0.20–0.86% (Table 6). For the flowering period, the R^2, mAE, and nRMSE of most observation stations ranged from 0.46–0.91, 3–5 days, and 0.01–5.6%, respectively (Table 6). Furthermore, for the maturity period, the R^2, mAE, and nRMSE of most observation stations ranged from 0.53–0.93, 2–5 days, and 0.88–6.7%, respectively (Table 6).

3.2. Yield simulation

Based on the results of formula (1), 2 and (3), Figure 7 show the comparison result for the observed value and simulated value of winter wheat yield in Shandong Province. The R^2, D-index, mRE, and nRMSE were 0.48, 0.82, 10.5% and 12.8%, respectively (Figure 7). On the basis of the results of formula (1), 2 and (3), Table 7 shows the evaluation indexes for the simulated annual yield values at each observation station. For most observation stations, the D-index, RE, and nRMSE ranged from 0.36–0.99, 3.3–18.9%, and 3.9–19.1%, respectively (Table 7).

The applicability of the drought simulation of the model was evaluated by the results of the moisture control test. Based on the results of formula (1), 2 and (3), Table 8 shows the simulation of winter wheat

Table 4. The parameters of single and comprehensive factors affecting potential yield.

Parameters	Biological significances	Minimum value	Maximum value
AMAXTB	Maximum leaf CO_2 assimilation rate as a function of development stage of the crop ($kg \cdot hm^{-2} \cdot h^{-1}$)	1	70
SLATB	Specific leaf area as a function of development stage ($hm^2 \cdot hm^{-1}$)	0.0007	0.0042
SPAN	Life span of leaves growing at 35 °C (d)	17	50
RGRLAI	Maximum relative increase in leaf area index ($hm^2 \cdot hm^{-2} \cdot d^{-1}$)	0.007	0.5
LAIEM	Leaf area index at emergence ($hm^2 \cdot hm^{-2}$)	0.0007	0.3
TDWI	Initial total crop dry weight ($kg \cdot hm^{-2}$)	0.5	300
FLTB	Fraction of above ground dry matter increase partitioned to leaves as a function of development stage ($kg \cdot kg^{-1}$)	0	1
FSTB	Fraction of above ground dry matter increase partitioned to stems as a function of development stage ($kg \cdot kg^{-1}$)	0	1
FRTB	Fraction of total dry matter increase partitioned to roots as a function of development stage ($kg \cdot kg^{-1}$)	0	1
FOTB	Fraction of above ground dry matter increase partitioned to storage organs as a function of development stage ($kg \cdot kg^{-1}$)	0	1
TMPFTB	Reduction factor of AMAX as function of average temperature (°C)	0	1
RDRRTB	Relative death rate of roots as a function of development stage ($kg \cdot kg^{-1} \cdot d^{-1}$)	0	0.02

Table 5. The parameters of water-limited affecting potential yield.

Parameters	Biological significances	Minimum value	Maximum value
CFET	Correction factor for evapotranspiration in relation to the reference crop	0.8	1.2
RDMCR	Maximum rooting depth of mature crop (cm)	50	400
PERDL	Maximum relative death rate of leaves due to water stress ($kg \cdot kg^{-1} \cdot d^{-1}$)	0	0.1
DEPNR	Crop group number for soil water depletion	1	5

yield under drought stress. The results show that the model could adequately simulate the yield reduction trend after drought stress, with the R^2, D-index, mRE, and nRMSE being 0.77, 0.93, 7.1%, and 7.4%, respectively.

For the simulation of the main growth period and yield formation under both normal and drought stress condition, the evaluation indexes were all within the acceptable range. Thus, the applicability evaluation and drought validation of the WOFOST model were completed for simulating the growth and yield formation of winter wheat in Shandong Province.

3.3. Evaluation index system

From this, to build an evaluation index system, the quantitative evaluation of the total above ground production (TAGP), maximum leaf area index (MAXLAI), total dry weight of leaves (TWLV), and total dry weight of stems (TWST) were carried out by the simulated result of the WOFOST model under different drought levels. Four drought treatments were set up in the water requirement period of winter wheat (from the jointing period to the flowering period). The relative soil humidity of treatment 1 (W1), treatment 2 (W2), treatment 3 (W3), and treatment 4

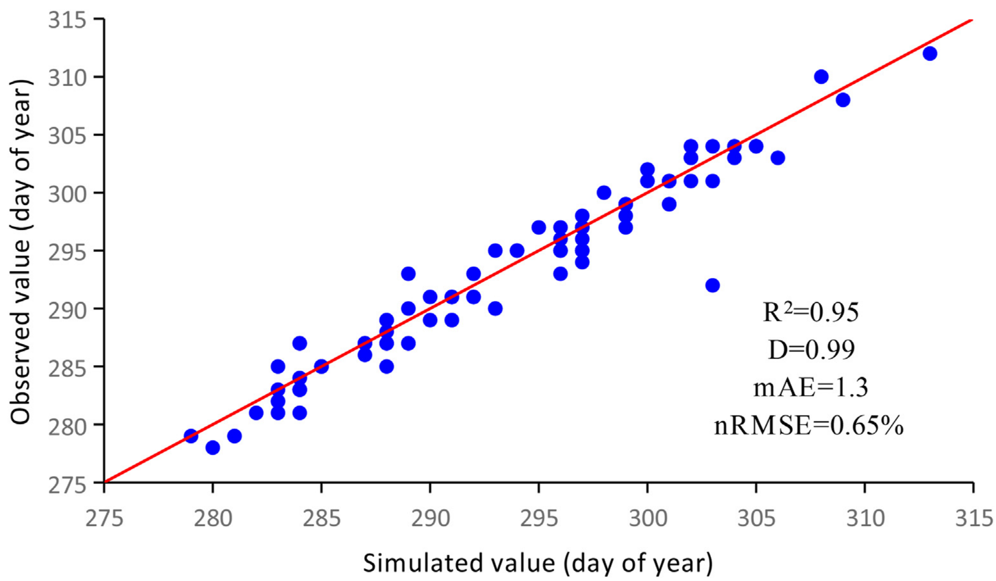

Figure 4. The comparison result for the observed value and simulated value of the seedling period of winter wheat in Shandong Province.

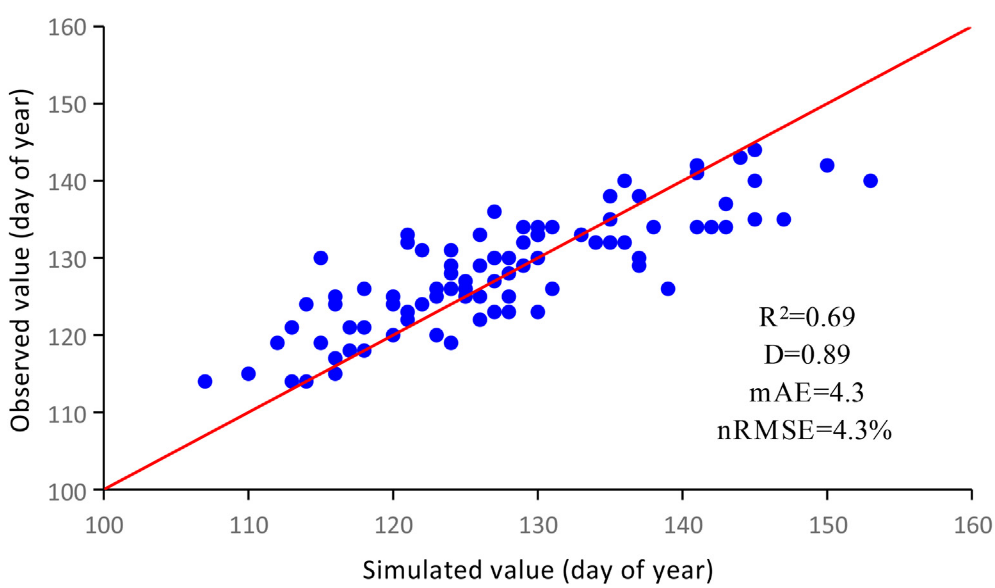

Figure 5. The comparison result for the observed value and simulated value of the flowering period of winter wheat in Shandong Province.

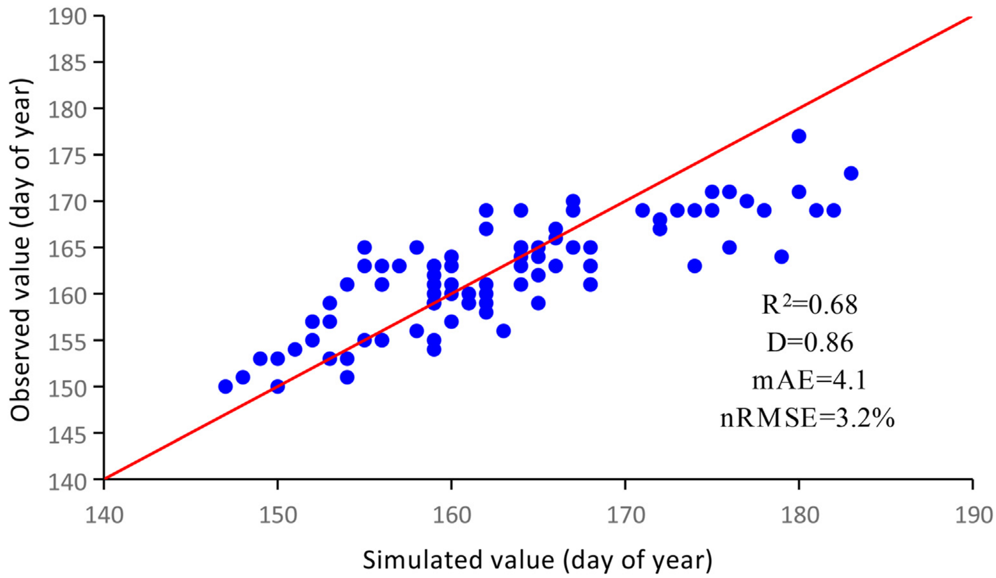

Figure 6. The comparison result for the observed value and simulated value of the maturity period of winter wheat in Shandong Province.

Table 6. The simulation results for the seedling period, flowering period, and maturity period of winter wheat at each observation station of Shandong Province.

Station	Seedling period			Flowering period			Maturity period		
	R^2	mAE (day)	nRMSE (%)	R^2	mAE (day)	nRMSE (%)	R^2	mAE (day)	nRMSE (%)
Laiyang	0.92	1	0.75	0.73	6	4.1	0.93	6	3.2
Wendeng	0.95	1	0.73	0.63	5	4.4	0.73	6	3.7
Fushan	0.99	2	0.73	0.70	5	5.6	0.87	5	3.3
Laizhou	0.89	1	0.20	0.91	3	2.6	0.81	4	2.3
Jiaozhou	0.95	1	0.64	0.56	5	4.3	0.83	5	2.5
Weifang	0.94	2	0.77	0.76	4	3.6	0.85	3	2.6
Zibo	0.91	1	0.59	0.35	4	1.4	0.21	4	2.8
Taian	0.77	2	0.20	0.69	3	0.01	0.59	3	0.88
Juxian	0.95	1	0.33	0.91	–	13.9	0.71	9	6.7
Linyi	0.86	2	0.86	0.04	4	3.4	0.57	4	2.2
Jining	0.06	3	0.54	0.48	3	2.2	0.78	2	1.7
Heze	0.98	1	0.33	0.46	5	4.2	0.36	4	2.8
Caoxian	0.92	1	0.72	0.66	3	2.9	0.53	3	2.4
Huimin	0.81	1	0.20	0.66	7	4.9	0.67	2	1.8
Dezhou	0.98	1	0.39	0.78	3	2.0	0.88	2	1.7
Liaocheng	0.94	1	0.48	0.76	5	3.6	0.65	4	2.0

(W4) of the water requirement period were 47–81%, 36–75%, 33–70%, and 28–66%, respectively (Table 9). The relative soil humidity of other periods was set to 82% or above.

And then, the RR were used to assess the impacts of drought. On the basis of the results of formula (5), the results (Table 10) show that TAGP, MAXLAI, TWLV, and TWST all had a significant decreasing trend with the aggravation of drought, with their RR being 13.6–41.0%, 37.8–56.5%, 19.4–42.1%, and 20.3–51.2%, respectively. Thus, the WOFOST crop model could be used to determine the drought degree based on the relative soil humidity and to determine the reduction of each winter wheat growth indicator with increasing drought intensity.

4. Discussion

In this study, the evaluation indexes of the simulation results for each growth period were in the acceptable range. However, the AE value of the seedling period was relatively small, while those of the flowering period and maturity period were relatively large. The reason may be that this research lacked the simulation of the wintering period and returning green period, and they were not specially defined in the WOFOST model (Supit et al., 1994). During the wintering period, winter wheat may lose biomass, which would affect the final yield. To improve the simulation accuracy for the flowering period, maturity period and yield, it is necessary to perform simulations for the wintering period and returning green period in further research.

In Figure 4, we found that one point is far away from the 1:1 line. This point is the seedling period in Jining in 2010. The actual day of year of seedling period was 292 in 2010, and the simulated result was 303. October 2010 in Jining was very special. There was no precipitation for a whole month. In order to ensure proper sowing time and emergence rate, the seeds of winter wheat were soaked before sowing. And the irrigation was increased to ensure adequate soil moisture. With the suitable temperature, the actual emergence time in 2010 is obviously earlier than that in other years. At the same time, accumulated temperature was mainly considered in the WOFOST model to drive the beginning of each development stage. So there's an outlier like this.

Besides the assessment indexes selected in this study, leaf area index (LAI) is also one of the important growth and development indicators of

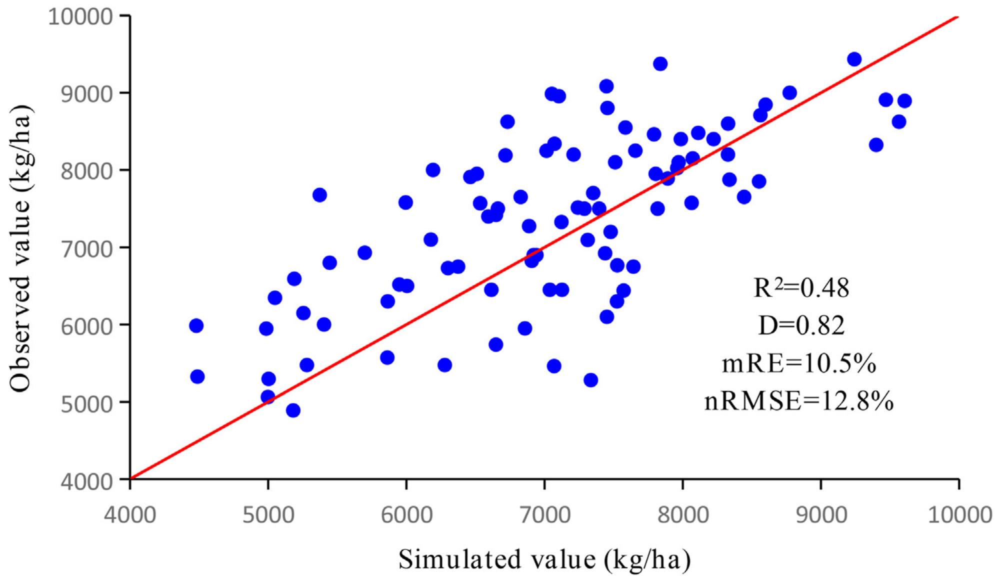

Figure 7. The comparison result for the observed value and simulated value of winter wheat yield in Shandong Province.

Table 7. The simulation results of winter wheat yield at each observation station of Shandong Province.

Station	D	RE (%)	nRMSE (%)
Laiyang	0.42	9.7	11.2
Wendeng	0.36	11.2	14.7
Fushan	0.17	15.5	16.8
Laizhou	0.80	3.3	3.9
Jiaozhou	0.59	11.0	13.1
Weifang	0.49	4.8	6.2
Zibo	0.19	11.9	15.0
Taian	0.74	11.6	12.9
Juxian	0.49	7.7	9.5
Linyi	0.95	18.9	19.1
Jining	0.74	6.6	8.3
Heze	0.99	10.8	11.9
Caoxian	0.17	16.2	17.4
Huimin	0.77	7.9	9.3
Dezhou	0.39	11.4	14.3
Liaocheng	0.81	12.4	10.8

Table 8. The simulation results of winter wheat yield under drought stress at the Taian agrometeorological experimental station.

Treatment	Observed value ($kg\cdot hm^{-2}$)	Simulated value ($kg\cdot hm^{-2}$)
CK	8641.6	8023.0
T1	7242.8	7710.0
T2	6530.8	7062.0
T3	6097.3	6659.0
T4	5786.6	5514.0
R^2	0.77	
D	0.93	
mRE (%)	7.1	
nRMSE (%)	7.4	

crops. And it is a comprehensive indicator of light energy utilization and canopy structure. However, most agrometeorological observation stations are lack of LAI observation. So the applicability of WOFOST model for LAI simulation needs more field experiments and observation results to verify.

Table 9. The drought treatments of the water requirement period of winter wheat.

Treatment	Relative soil humidity (%)
W1	47–81
W2	36–75
W3	33–70
W4	28–66

Table 10. The reduction of growth indicators of winter wheat under four water treatment levels through WOFOST model.

Treatment	RR_{TAGP} (%)	RR_{MAXLAI} (%)	RR_{TWLV} (%)	RR_{TWST} (%)
W1	-13.6	-37.8	-19.4	-20.3
W2	-23.6	-44.3	-28.5	-33.4
W3	-28.7	-50.2	-33.0	-38.8
W4	-41.0	-56.5	-42.1	-51.2

Previous studies have shown that, several crop models are insensitive to extreme climate events (Asseng et al., 1998). And to a certain extent, they cannot fully reflect the impacts of disaster incidents on agricultural production. Especially for extreme drought years, the accuracy of model simulation is significantly reduced. In this study, the WOFOST model has a simulation module for drought. Moreover, its simulation performance on drought has been verified in many crops of different regions (Zhang et al., 2013; Yang et al., 2020; Dong et al., 2020).

From Table 8, we can find that the simulated results of T1, T2 and T3 are higher than the observed results. And the simulated result of T4 and CK are lower than the observed results. The reason that T1, T2 and T3 are higher may be the simulated results of winter wheat returned to normal growth level immediately after relieving drought stress. But for the actual observed results of winter wheat, it need to gradually return to the normal growth level. The reason that T4 is lower may be the degree of drought exceeded the stress threshold in the model algorithm. And it result in greater damage on winter wheat growth and development. The reason that CK is lower may lie in the basic parameters. The simulation results of yield of Taian were compared from 2010 to 2015. And the simulated results were smaller than the observed results in four years. The more accurate reasons need to be explained by more experiments.

Besides the WOFOST model, the APSIM and DSSAT are another crop mechanism models with wide application range and good simulation effects. Relevant scholars have completed the applicability evaluation of these models for winter wheat simulation in Shandong Province (Li et al., 2012; Xu et al., 2015). Soil is the core of the APSIM model. And the target of this model is to simulate the continuous changes characteristics of soil caused by weather, crops and management practices (Cao et al., 2011). The APSIM model could facilitate the comparison between different modules, which has a good effect on making production decision. The DSSAT model considers the influence of various factors on growth and development of crops, including genetic characteristics of crops, management practices, environment, nitrogen and water stress, pests and diseases (Jones et al., 2003). And this model is mainly used in yield forecasting, soil water and fertilizer management and so on. In comparison, the WOFOST model has the higher explanatory and mechanistic. And its advantages are more obvious in considering the response of crop growth process to different climatic conditions and different geographical locations.

Factors such as diseases, insect pests, and extreme climatic events (e.g., late frost damage, dry hot wind, continuous rain) also have a great impact on the growth and yield of winter wheat. However, these factors are not fully considered in the WOFOST model (Hou et al., 2018). Therefore, the impacts of diseases, insect pests, and extreme climatic events on the simulation results of the WOFOST model require further study. Existing studies of relative experimental design and optimization methods (Donatelli et al., 2017; Jones et al., 2017; Zhang et al., 2006; Li et al., 2020) would provide appropriate references for this purpose.

5. Conclusion

The study region is divided into five parameters adjustment areas to obtain the more accurate simulation results. And the problem is solved about the low spatial simulation accuracy caused by single parameter. For the simulation of the seedling period, flowering period, and maturity period of winter wheat in Shandong Province, the R^2 were 0.95, 0.69, and 0.68 respectively. The D-index were 0.99, 0.89, and 0.86 respectively. The mAE were 1.3, 4.3, and 4.1 respectively. And the nRMSE were 0.65%, 4.3%, and 3.2%, respectively. For the yield simulation, the R^2, D-index, mRE, and nRMSE was 0.48, 0.82, 10.5% and 12.8%, respectively. For the yield simulation under drought stress, the R^2, D-index, mRE, and nRMSE were 0.77, 0.93, 7.1%, and 7.4%, respectively. All indexes were within the acceptable range, showing that this model could simulate the formation process of winter wheat yield under both normal and drought conditions. With the aggravation of drought from the jointing period to the flowering period, the growth indicators of winter wheat showed a decreasing trend, with the TAGP, MAXLAI, TWLV, and TWST decreasing by 13.6–41.0%, 37.8–56.5%, 19.4–42.1%, and 20.3–51.2%, respectively.

Declarations

Author contribution statement

Dong Zhiqiang: Conceived and designed the experiments; Performed the experiments; Analyzed and interpreted the data; Wrote the paper.

Jiang Mengyuan: Conceived and designed the experiments; Performed the experiments; Analyzed and interpreted the data.

Xue Xiaoping: Conceived and designed the experiments; Wrote the paper.

Pan Zhihua: Analyzed and interpreted the data; Wrote the paper.

Li Nan: Performed the experiments; Contributed reagents, materials, analysis tools or data.

Zhao Hong: Contributed reagents, materials, analysis tools or data.

Hou Yingyu: Conceived and designed the experiments; Contributed reagents, materials, analysis tools or data.

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Data availability statement

The authors do not have permission to share data.

Declaration of interests statement

The authors declare no conflict of interest.

Additional information

No additional information is available for this paper.

References

Bregaglio, S., Frasso, N., Pagani, V., et al., 2015. New multi-model approach gives good estimations of wheat yield under semiarid climate in Morocco. Agron. Sustain. Dev. 35 (1), 157–167.
Cao, H.X., Zhao, S.L., Ge, D.K., et al., 2011. Discussion on development of crop models. Sci. Agric. Sin. 44 (17), 3520–3528.
Castaneda Vera, A., Leffelaar, P.A., Alvaro Fuentes, J., et al., 2015. Selecting crop models for decision making in wheat insurance. Eur. J. Agron. 68, 97–116.
Ceglar, A., Van der Wijngaart, R., De Wit, A., et al., 2019. Improving WOFOST model to simulate winter wheat phenology in Europe: evaluation and effects on yield. Agric. Syst. 168, 168–180.
Chen, Z.L., Zhang, J.P., Wang, C.Y., et al., 2007. Application of WOFOST model in simulation of integrated impacts of low temperature and drought on maize yield. Chin. J. Agrometeorol. (4), 440–442.
Confalonieri, R., 2010. Monte Carlo based sensitivity analysis of two crop simulators and considerations on model balance. Eur. J. Agron. 33 (2), 89–93.
Cui, Y.K., Wang, N.N., Tian, Z.W., et al., 2019. Effect of water deficit during tillering and jointing stages on nitrogen accumulation and translocation in winter wheat. J. Triticeae Crops 39 (3), 323–328.
De Wit, A., Boogaard, H., Fumagalli, D., et al., 2019. 25 years of the WOFOST cropping systems model. Agric. Syst. 168, 154–167.
Donatelli, M., Magarey, R.D., Bregaglio, S., et al., 2017. Modelling the impacts of pests and diseases on agricultural systems. Agric. Syst. 155, 213–224.
Dong, Z.Q., Wang, M.M., Li, H.Y., et al., 2019. Applicability assessment of WOFOST model of growth and yield of summer maize in Shandong province. Crops (5), 159–165.
Dong, Z.Q., Li, M.H., Li, N., et al., 2020. The thresholds of soil drought and its impacts on summer maize in Shandong province. Sci. Agric. Sin. 53 (21), 4376–4387.
Gao, Y.G., Wang, Y.G., Yin, S.P., et al., 2006. The application of World food study model (WOFOST) for yield prediction in heilongjiang province. Chin. J. Agrometeorol. 27 (1), 27–30.
Gilardelli, C., Confalonieri, R., Cappelli, G.A., et al., 2018. Sensitivity of WOFOST-based modelling solutions to crop parameters under climate change. Ecol. Model. 368, 1–14.
Guo, J.P., 2015. Advances in impacts of climate change on agricultural production in China. J. Appl. Meteorol. Sci. (1), 1–11.
Hou, X.H., Sui, X.Y., Yao, H.M., et al., 2019. Response of winter wheat phenology to climate change in Norther China. J. Triticeae Crops 39 (2), 202–209.
He, L., Hou, Y.Y., Zhao, G., et al., 2016. Parameters optimization of WOFOST model by integration of global sensitivity analysis and Bayesian calibration method. Trans. Chin. Soc. Agric. Eng. 32 (2), 169–179.
Huang, J.X., Jia, S.L., Ma, H.Y., et al., 2017. Dynamic simulation of growth process of winter wheat in main production areas of China based on WOFOST model. Trans. Chin. Soc. Agric. Eng. 33 (10), 222–228.
Hou, Y.Y., He, L., Jin, N., et al., 2018. Establishment and application of crop growth simulating and monitoring system in China. Trans. Chin. Soc. Agric. Eng. 34 (21), 165–175.

IPCC, 2013. Climate Change 2013: the Physical Science Basis. Cambridge University Press, Cambridge, Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change.
Jiang, Z.W., Chen, Z.X., Zhou, Q.B., et al., 2011. Global sensitivity analysis of CERES-Wheat model parameters. Trans. Chin. Soc. Agric. Eng. 27 (1), 236–242.
Jin, X.X., Yao, Y.R., Jia, X.L., et al., 2019. Effects of genotype and environment on wheat yield, quality, and nitrogen use efficiency. Acta Agron. Sin. 45 (4), 635–644.
Jones, J.W., Hoogenboom, G., Porter, C.H., et al., 2003. The DSSAT cropping system model. Eur. J. Agron. 18, 235–265.
Jones, J.W., Antle, J.M., Basso, B., et al., 2017. Brief history of agricultural systems modeling. Agric. Syst. 155, 240–254.
Kothari, K., Ale, S., Attia, A., et al., 2019. Potential climate change adaptation strategies for winter wheat production in the Texas High Plains. Agric. Water Manag. 225, 105764.
Li, K.N., Yang, X.G., Liu, Y., et al., 2012. Distribution characteristics of winter wheat yield and its influenced factors in North China. Acta Agron. Sin. 38 (8), 1483–1493.
Li, S., Zhang, L., Huang, B.X., et al., 2020. A comprehensive index for assessing regional dry-hot wind events in Huang-Huai-Hai Region, China. Phys. Chem. Earth. 116 (6), 102860.
Liu, C., Zhang, R.H., Zhao, X.W., et al., 2020. Climate change and its effect on the yields of winter wheat and summer corn in Shandong province. Res. Soil Water Conserv. 27 (3), 379–384.
Liu, B.C., Liu, W.P., Mei, X.R., et al., 2006. Prospects for crop growth models introduced into agrometeorology services in China. Meteorol. Mon. (12), 12–17.
Liu, Y., Chen, Q., Ge, Q., et al., 2018. Modelling the impacts of climate change and crop management on phenological trends of spring and winter wheat in China. Agric. For. Meteorol. 248, 518–526.
Luan, Q.Z., Ye, C.H., Mo, Z.H., et al., 2014. Maize yield loss assessment for drought based on WOFOST model: a Case Study in Beijing. Chin. J. Agrometeorol. 35 (3), 311–316.
Lv, Z., Liu, X., Cao, W., et al., 2013. Climate change impacts on regional winter wheat production in main wheat production regions of China. Agric. For. Meteorol. 171, 234–248.
Ma, Y.P., Wang, S.L., Zhang, L., et al., 2005. A preliminary study on the re-initialization/re-parameterization of a crop model based on remote sensing data. Acta Phytoecol. Sin. 29 (6), 918–926.
National Bureau of Statistics, 2019. China Statistical Yearbook. China Statistical Press, Beijing.
Osborne, T.M., Lawrence, D.M., Challinor, A.J., et al., 2010. Development and assessment of a coupled crop-climate model. Global Change Biol. 13 (1), 169–183.
Qu, C., Li, X., Hui, J.U., et al., 2019. The impacts of climate change on wheat yield in the Huang-Huai-Hai Plain of China using DSSAT-CERES-Wheat model under different climate scenarios. J. Integr. Agric. 18 (6), 1379–1391.
Ren, S.Y., Zhang, Q.S., Li, T.Y., et al., 2019. Spatiotemporal variation of winter wheat yield and nitrogen management in five provinces of North China Plain. Sci. Agric. Sin. 52 (24), 4527–4539.
Sun, X.S., Long, Z.W., Song, G.P., et al., 2017. Effects of climate change on cropping pattern and yield of summer maize-winter wheat in Huang-Huai-Hai Plain. Sci. Agric. Sin. 50 (13), 2476–2487.
Sun, L.L., Hou, Q., Ma, Y.P., et al., 2016. Adaptability of WOFOST model to simulate the whole growth period of maize in Hetao irrigation region of Inner Mongolia. Chin. J. Ecol. 35 (3), 800–807.
Supit, I., Hooijper, A.A., van Diepen, C.A., 1994. System Description of the WOFOST6.0 Crop Simulation Model Implemented in CGMS, Volume 1: Theory and Algrorithms. The Winand Starting Centre for Integrated Land, Soil and Water Research (SC - DLO). Wageningen, the Netherlands.
Van Diepen, C.A., Wolf, J., Van Keulen, H., et al., 1989. WOFOST: a simulation model of crop production. Soil Use Manag. 5 (1), 16–24.
Wang, J., Wang, E., Feng, L., et al., 2013. Phenological trends of winter wheat in response to varietal and temperature changes in the North China Plain. Field Crop. Res. 144 (6), 135–144.
Wang, R., Li, Y.F., Zhang, L.J., et al., 2015. WOFOST model based on soil moisture driven and its adaptability. Chin. J. Agrometeorol. 36 (3), 263–271.
Wu, J., Yu, F.S., Chen, Z.X., et al., 2009. Global sensitivity analysis of growth simulation parameters of winter wheat based on EPIC model. Trans. Chin. Soc. Agric. Eng. 25 (7), 136–142.
Xiao, D.P., Tao, F.L., Shen, Y.J., et al., 2014. Sensitivity of response of winter wheat to climate change in the North China Plain in the last three decades. Chin. J. Eco-Agric. 22 (4), 430–438.
Xie, W.X., Yan, L.J., Wang, G.H., 2006. Simulation and validation of rice potential growth process in Zhejiang by utilizing WOFOST model. Chin. J. Rice Sci. 20 (3), 319–323.
Xing, A., Zhuo, Z.Q., Zhao, Y.Z., et al., 2020. Sensitivity analysis of WOFOST model crop parameters under different production levels based on EFAST method. Trans. Chin. Soc. Agric. Mach. 51 (2), 161–171.
Xing, H.M., Xiang, S.Y., Xu, X.G., et al., 2017. Global sensitivity analysis of AquaCrop crop model parameters based on EFAST method. Sci. Agric. Sin. 50 (1), 64–76.
Xu, J.W., Ju, H., Mei, X.R., et al., 2015. Simulation on potential effects of drought on winter wheat in Huang-Huai-Hai Plain from 1981 to 2010. Trans. Chin. Soc. Agric. Eng. 31 (6), 150–158.
Yan, Y.L., Hao, W.P., Mei, X.R., et al., 2011. Effects of water stress-rewatering at jointing stage on dry matter accumulation and WUE of winter wheat. Chin. J. Agrometeorol. 32 (2), 190–195.
Yang, F.Y., Zheng, Q.H., Li, W.K., 2020. Risk assessment of drought damage of spring maize in Liaoning Province based on WOFOST model. Agric. Res. Arid Areas 38 (6), 218–225.
Yang, Y.C., Wang, J.L., Song, Y.P., 2013. Introduction of WOFOST crop growth simulation model mechanism and its use. Adv. Meteorol. Sci. Technol. 3 (5), 29–35.
Yuan, Z., Yan, D.H., Yang, Z.Y., et al., 2015. Temporal and spatial variability of drought in huang-huai-hai river basin, China. Theor. Appl. Climatol. 122 (3-4), 755–769.
Zhang, J.B., Xue, X.P., Li, N., et al., 2019. Effect of drought stress on physiological characteristics and dry matter production of winter wheat during water critical period. Desert Oasis Meteorol. 13 (3), 124–130.
Zhang, J.P., Zhao, Y.X., Wang, C.Y., et al., 2013. Evaluation technology on drought disaster to yields of winter wheat based on WOFOST crop growth model. Acta Ecol. Sin. 33 (6), 1762–1769.
Zhang, X.F., Yu, W.D., Wang, C.Y., et al., 2006. Application of WOFOST model to assessment of winter's chilling damage by late frost. J. Nat. Disasters 15 (6), 137–141.