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The effects of CO_2 database on a localized AquaCrop model construction based on the field experiment

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Abstract: To examine whether the use of default CO_2 database affected the simulation results, this paper built the AquaCrop models of winter wheat based on the measured CO_2 database and the default CO_2 database, respectively. The models were calibrated with data (2017–2018) and validated with the data (2018-2019) in the North China Plain. The residual coefficient method (CRM), root mean square error (RMSE), normalized root mean square error (NRMSE) and determination coefficient (R^2) were used to test the model performance. The results showed that the accuracy of simulation under the two CO_2 database were both good. Compared with the default CO_2 database, the simulation accuracy under the measured CO_2 database had higher accuracy. In order to verify the model further, the simulated values of evapotranspiration, soil water content and measured values were compared and analyzed. The results showed that there were some errors between the measured evapotranspiration and the values of simulation in the filling and waxing period of winter wheat. In general, the simulation values of

evapotranspiration were consistent with the measured value at different irrigation levels. The simulated values of the soil water content at the three levels of irrigation were all higher than the measured values, but the simulated results basically reflected the dynamic changes of soil water content throughout the growth period. The model adjustment value of WP*(the normalized water productivity) were a difference under the two CO_2 databases, which is one of the reasons for the difference in the simulation results. The results show that in the absence of measured CO_2 data, the default CO_2 database can be used, which has little influence on the model construction, and the accuracy of the model constructed meets the actual demand. The research results can provide a basis for the establishment of crop models in North China Plain.

Keywords: AquaCrop model; Winter wheat; CO_2; Evapotranspiration; Soil water content

1 Introduction

The water on the earth is about 1.4 billion km^3, however, the available water is less than 45,000 km^3 (about 0.003% of the total), and only 9,000 to 14,000 km^3 (about 0.001% of the total) suitable for human use. At present, about 1.5 billion people are facing a shortage of fresh water in more than 80 countries around the world, of which 300 million people in 26 countries are living in a state of water shortage. It is estimated that 3 billion people in the world will be short of water, involving more than 40 countries and regions by 2025. In the 21st century, water resource is becoming a precious and scarce resource. The problem of water resource is not only a matter of resources, but a major strategic issue that relates to the sustainable development of the country's economy, society, and long-term security. China, the world's most populous developing country, feeds 22% of the world's population with 7% of the world's land and 8% of its fresh water. However, as the population continues to grow, the climate is arid, pollution continues to worsen, and water and arable land resources continue to decrease, China will face huge pressures and challenges in terms of water resources and food security (Zhang et al.2005). The North China Plain covers an area of 0.44×10^6 km^2 and has a population of over 200 million. It is one of the most productive and intensive agricultural areas in China (Iqbal et al. 2014). The main crops are wheat and corn. The wheat and corn production account for 20% of the country's total output, of which wheat accounts for 11% and corn accounts for 9%. Due to the growth cycle of winter wheat from October to June of the second year, it is the time when water is supplied the most

58 insufficient in North China, a large amount of groundwater has been over-exploited for
59 irrigation. There is a more prominent contradiction between water resources and food
60 security issues in North China. To solve water resources and food security issues, it is
61 necessary to build a water-driven crop growth model to simulate and formulate a
62 reasonable future adjustment schemes of food crops pattern (Xia et al. 2004).

63 At present, a series of crop growth models have been developed, such as CERES-
64 Maize (Kisekka et al. 2016), WOFOST (Diepen et al. 2007), CropSyst (Stockle et al.
65 2003), DSSAT-CSM (Jones et al. 2003), and the Hybrid Maize model (Yang et al. 2004).
66 However, due to the complexity of these models and the large number of input
67 parameters, it is difficult to use such models for popularization and application (Malik
68 et al. 2017). The Food and Agriculture Organization (FAO) of the United Nations
69 developed the AquaCrop model in 2009. Compared with above models, AquaCrop is
70 user-friendly and practitioner-oriented software (Ahmadi et al. 2015). The AquaCrop
71 model has been extensively tested and applied in different regions (Raes et al. 2009;
72 Bird et al. 2016; Li et al. 2019). The main problem of the AquaCrop model is the
73 applicability. Hsiao et al. (2009) concluded that the applicability of the AquaCrop
74 model should be further verified for different soil properties, crop characteristics and
75 climatic conditions around the world. Yin et al. (2013) studied the applicability of the
76 AquaCrop model in semi-arid regions and applied the AquaCrop model to the
77 management of deficient irrigation of spring wheat, and got irrigation regimes in
78 different years. Iqbal et al. (2014) studied the applicability of the AquaCrop model in

the North China Plain and simulated winter wheat biomass, yield, actual evapotranspiration and total soil water content (0-120 cm). Mhizhat et al. (2014) calibrated the AquaCrop model by using measured corn data, and simulated yield through an optimized program. Sylaios (2016) used nine years of climate data from Northern Greece and a locally calibrated AquaCrop model to test an efficient model-based procedure for computing seasonal sub-optimal irrigation schedules. Sandhu and Irmak (2019) evaluated the AquaCrop model relative to maize growth, yield, and water use parameters/variables under different water stress conditions over six years (2005-2010) in Nebraska, USA. Li et al. (2019) studied the applicability of the model in North China Plain and applied the AquaCrop model to optimize irrigation strategies.

The above researchers run the AquaCrop model with the default CO_2 database (MaunaLoa.CO2 file). When the measured CO_2 database are missing, AquaCrop will automatically apply the default CO_2 database. Actually, the CO_2 concentration had effects on crop growth (Xiao et al. 2005; Meng et al. 2015; Ma et al. 2005; Li et al. 2020). In this study, a local Aquacrop model was established to simulate the biomass and yield of winter wheat based on the measured and default CO_2 database, and analyze how much influence the default database can have on the simulation results of the model in North China Plain.

2 Materials and methods

2.1 Study Area

The North China Plain (NCP) is one of the most productive agricultural regions in China. The 70% of the water used in the wheat-growing seasons comes from groundwater pumped from wells with a depth of over 40 m, causing a rapid decline in the groundwater table in the NCP (Yuan et al. 2013). With climate change in the NCP, the contradiction between water resources and agricultural water demand will be further intensified (Falloon et al. 2010).

The study area is located in the NCP and its coordinate is 37°30′~38°18′ N and 114°19′~116°30′ E, with an average altitude of 42 m (Fig. 1). The annual rainfall is 455.8mm, which is concentrated in June to September, and mean annual evaporation is approximately 1000~1200 mm, which is characteristic of a semi-arid sub-humid monsoon climate with the average annual temperature of 13.3℃, the average number of sunshine hours of 2397.2 h and the annual frost-free period of 236 d.

The selected cultivar of winter wheat was Guan-35, the seeding rate was 187.5 $kg \cdot ha^{-1}$. The sowing time was in mid to late October of each year, and the harvest time was in early June of the next year. The winter wheat planting time for the 2017-2018 season and 2018-2019 season were October 28 and October 17, respectively. There were nine test plots, each with an area of 8 m×15 m. The irrigation mode was border irrigation, which was carried out in the wintering period, jointing period and grouting period respectively. Before sowing, a compound fertilizer was applied as the base

118 fertilizer, and the fertilizer amount was 750kg/hm^2. The tillage mode was rotary tillage.
119 The irrigation schedule of winter wheat for 2017-2019 was shown in Table 1. T1 is 100%
120 of the local irrigation level, T2 is 80% of the local irrigation level, and T3 is 60% of the
121 local irrigation level in Table1.

122 2.2 Description of AquaCrop Model

123 The principle of AquaCrop model was the crop yield-water effect relationship
124 proposed by Doorenbos and Kassam (1979), which was expressed as follows:

125 $$\frac{Y_m - Y_a}{Y_m} = K_y \left(\frac{ET_m - ET_a}{ET_m}\right) \quad (1)$$

126 Where Y_m and Y_a are the maximum output (kg • m^{-2}) and actual output (kg·m^{-2}),
127 respectively; ET_m is the maximum evapotranspiration (mm) and ET_a is actual
128 evapotranspiration (mm); K_y is the crop yield response factor (dimensionless).

129 In AquaCrop, ET is decomposed into E and Tr, which can avoid the interference of
130 soil evaporation on crop yield, especially when the canopy coverage is reached the
131 maximum (CCmax). The core formula of AquaCrop are as follows (Steduto et al. 2009):

132 $$B = WP^* \cdot \sum \frac{T_r}{ET_0} \quad (2)$$

133 $$Y = B \cdot HI \quad (3)$$

134 Where WP^* is the normalized crop water productivity (g • m^{-2}), and its value varies
135 with the annual average CO_2 concentration and the difference in crop species; B is the
136 cumulative aboveground biomass production (g • m^{-2}); Tr is the daily crop transpiration

(mm • day^{-1}); ET_0 is the daily reference evapotranspiration (mm • day^{-1}); Y is the yield production (g • m^{-2}); and HI is the harvest index (%).

In AquaCrop model, the aboveground biomass is simulated by the normalized water productivity (WP*) (Eq.2). The WP* is normalized for atmospheric CO_2 concentration, using the annual mean CO_2 concentration measured at Mauna Loa Observatory, Hawaii, for each of the years. The year 2000, with its mean CO_2 concentration of 369.41 ppm, is chosen as the reference year for CO_2. AquaCrop will adjust WP* when running a simulation for a year at which the atmospheric CO_2 concentration differs from its reference value (369.41 ppm). The adjustment is obtained by multiplying WP* with the correction coefficient f_{CO2} (Vanuytrecht et al., 2011). The coefficient considers the difference between the reference value and the atmospheric composition for that year:

$$WP^*_{adj} = f_{CO2} WP^* \tag{4}$$

$$f_{CO2} = \frac{([CO2]_i/[CO2]_o)}{1 + ([CO2]_i - [CO2]_o)[(1-w)b_{sted} + w(f_{sink}b_{sted} + (1-f_{sink})b_{FACE})]} \tag{5}$$

$$0 \le w = (1 - \frac{550 - [CO2]_i}{550 - [CO2]_o}) \le 1 \tag{6}$$

where WP^*_{adj} is WP adjusted for CO_2; f_{CO2} is correction coefficient for CO_2; $[CO2]_o$ is reference atmospheric CO_2 concentration (369.41 ppm);$[CO2]_i$ is actual atmospheric CO_2 concentration for year i (ppm); the value of b_{sted} is 0.000138 (Steduto et al., 2007); b_{FACE} is 0.001165 (derived from FACE experiments); w is weighing factor, the threshold of 550 ppm is selected as the representing value for the elevated CO_2

maintained in the FACE experiments; f_{sink} is crop sink strength coefficient. The value of f_{sink} is taken as zero in this study (based on an analysis of crop responses in FACE environments by Vanuytrecht et al., 2011).

2.3 Construction of the AquaCrop model

The most important parameters of crops included initial canopy coverage, threshold for extreme growth temperature, maximum effective root depth, and planting density. The soil parameters in the model included: saturated moisture content, permanent wilting point content, and initial value of field capacity etc., which need to be set according to the soil characteristics of the experimental fields.

Input model parameters

The soil texture in the experimental fields is loam. The depth of soil in the experimental fields is 0~120cm, which is divided into 6 layers with each layer thickness of 20 cm. The soil characteristics of each layer were shown in Table 2.

During the two-season winter wheat growth period of 2017-2019, soil samples of 0 ~ 60cm deep were collected every 5~10 days, and soil water content (SWC) was measured by sampling every 10cm. The SWC was measured before and after irrigation in the key growth stages of winter wheat (seeding period, overwintering period, jointing period, filling period and maturity period).

The meteorological data came from the data monitored by the automatic meteorological station installed in the experimental fields, of which data were recorded

at intervals of 30min, including temperature, relative humidity, wind speed at 2m altitude, duration of sunshine, atmospheric pressure, rainfall, heat flux, net radiation, etc. Reference evapotranspiration (ET_0) can be estimated by Penman-Monteith equation, and the ET_0 calculation software recommended by the Land and Water Division of FAO was applied to calculate the reference crop evapotranspiration.

$$ET_0 = \frac{0.408\Delta(R_n-G)+\frac{900}{T+273}U_2(e_s-e_a)}{\Delta+\gamma(1+0.34U_2)} \quad (7)$$

Where R_n is the net radiation on the crop surface ($MJ \cdot m^{-2} \cdot d^{-1}$); G is the soil heat flux ($MJ \cdot m^{-2} \cdot d^{-1}$),T is the average temperature (℃), U_2 is the average at a height of 2 m Wind speed ($m \cdot s^{-1}$), e_s is the saturated water pressure (kPa), e_a is the actual water pressure (kPa), Δ is the slope of the saturated water vapor pressure and temperature curve ($kPa \cdot ℃^{-1}$)， γ is the dry and wet surface constant ($kPa \cdot ℃^{-1}$).

An equipment, Agilent 5890 SERIES II gas chromatograph, can be applied to measure the CO_2 concentration in the experimental fields. The conditions for analyzing and detecting atmospheric CO_2 with 5890 SERIES II gas chromatograph: silica gel column (aged at 150℃ for 24h before measurement), injection temperature is 130℃, oven temperature is 120℃, detector temperature is 150℃.The carrier gas of TCD (thermal conductivity detection) is high purity N_2 (mol/mol, ≥99.999%)which flow velocity is 40ml/min; the sample volume of the gas is 1.0 ml, and the retention time of CO_2 peak area on the chromatogram is 1.5min.

Determination of CO_2 concentration: the CO_2 concentration of atmospheric samples were determined within 2 days by using the gas chromatograph. When the sample of

194 CO_2 was collected, the atmospheric temperature was recorded at the same time each
195 time. The gas samples were collected by using professional gas pump equipment
196 starting from 10 o'clock in the morning for a total of four times at each 20 minutes. The
197 gas sample was collected at each 5~7d, and the sample gas was added 2~3 times in case
198 of irrigation, fertilization, etc.

199 CO_2 concentration detection method: a standard gas with known CO_2 concentration
200 were injected into the gas chromatograph to obtain the stable peak area values of the
201 standard gas (the error of two consecutive peak areas is within 0.1%). The CO_2
202 concentration of the sample gas were detected based on the peak area and the known
203 CO_2 concentration of the standard gas.

204 The change curve of atmospheric CO_2 concentration in the two seasons of winter
205 wheat (2017-2018, 2018-2019 season) was shown (Fig.2). The two average
206 atmospheric CO_2 concentration during the growth period of winter wheat was
207 462.6ppm and 478.0 ppm, respectively. Based on the measured CO_2 concentrations, a
208 CO_2 database suitable for the local climatic conditions in the experimental fields was
209 established instead of the default CO_2 database (Maunaloa.CO_2) provided by the model
210 itself.

211 The AquaCrop provided physiological parameters for 14 crops including cotton,
212 corn, wheat, potato, rice etc. Some parameters were conservative parameters (Table 3).
213 Other winter wheat parameters need to be calibrated by AquaCrop model.

Model evaluation

The performance of the model was evaluated using the following indicators: the root mean square error (RMSE), residual coefficient method (CRM), normalized root mean square error (NRMSE) and determination coefficient (R^2).

$$RMSE = \sqrt{\sum_{i=1}^{n} \frac{(P_i - O_i)^2}{n}} \tag{8}$$

$$CRM = \frac{\sum_{i=1}^{n} O_i - \sum_{i=1}^{n} P_i}{\sum_{i=1}^{n} O_i} \times 100\% \tag{9}$$

$$NRMSE = \frac{100}{\bar{O}} \sqrt{\sum_{i=1}^{n} \frac{(P_i - O_i)^2}{n}} \tag{10}$$

$$R^2 = \left[\frac{\sum_{i=1}^{n} (O_i - \bar{O})(P_i - \bar{P})}{\sqrt{\sum_{i=1}^{n} (O_i - \bar{O})^2} \sqrt{\sum_{i=1}^{n} (P_i - \bar{P})^2}} \right]^2 \tag{11}$$

Where n is the total number of observations of the sample, O_i and P_i are the observations and simulation values, respectively. $\bar{O}$ and $\bar{P}$ are the average of all observation and simulation values, respectively. RMSE indicates the deviation between the observed value and the simulation value. The smaller the value is, the higher the accuracy of the model indicates. The smaller CRM value of the coefficient is, the better the simulation effect shows. When the value of NRMSE is less than 10%, the simulation effect is high. A value between 10% and 20% indicates that the simulation result is good, while between 20% and 30% indicates that the simulation effect is average. The value of R^2 ranges from 0 to 1, with values close to 1 indicating a good agreement, and typically values greater than 0.5 are considered acceptable in watershed simulations (Moriasi et al., 2007).

3 Results and discussion

3.1 Analysis of biomass and yield simulation results under two CO_2 databases

In order to analyze the differences in simulation results of using the various CO_2 databases, the default CO_2 database (Maunaloa.CO_2) and the measured CO_2 database were used to simulate. The results of the winter wheat biomass under different CO_2 databases were shown in Tables 4 and 6, respectively, and the results of the yield were shown in Tables 5 and 7 respectively.

The CRM values range of the winter wheat biomass simulation values in 2017-2018 season were -1.193%~1.844% under the default CO_2 database (Maunaloa.CO_2) in Table 4, and the values (2018-2019 season) were -0.676%~0.932%. The values of RMSE ranged from 0.037~0.257 $t \cdot ha^{-1}$ in 2017-2018 season, and the values (2018-2019 season) were 0.130~0.299 $t \cdot ha^{-1}$. The values of NRMSE (2017-2018 season) were 0.298%~1.948%, and the values (2018-2019 season) were 0.864% to 2.076%. The absolute CRM values were less than 2.0%, the values of RMSE were less than 0.300 $t \cdot ha^{-1}$, and the NRMSE values were less than 2.5%. Overall, the errors between the simulated and measured values of winter wheat biomass were small.

The range of CRM winter wheat (2017-2018 season) yield simulation values was -0.559% to -0.073%, and the range of CRM (2018-2019 season) was -0.059% to 3.049% under the default CO_2 database (Maunaloa.CO_2) in Table 5.The value of RMSE for winter wheat (2017-2018 season) was between 0.025 $t \cdot ha^{-1}$ and 0.142 $t \cdot ha^{-1}$, and the value (2018-2019 season) was in the range of 0.045~0.238 $t \cdot ha^{-1}$. The value of NRMSE

(2017-2018 season) ranged from 0.447% to 2.327%, and the value (2018-2019 season) ranged from 0.741% to 3.327%. The absolute CRM values were all less than 3.5%, the RMSE values were less than 0.25 $t \cdot ha^{-1}$, and the NRMSE values were less than 3.5%, which indicated that the precise of yield simulation were good. Overall, the errors between the simulated and measured values of winter wheat yield were small.

The CRM range of winter wheat (2017-2018 season) biomass simulation values was -0.727%~1.151%, and the CRM range (2018-2019 season) was -0.273% to 0.100% under the measured CO_2 database in Table 6. The values of RMSE ranged from 0.057~0.204 $t \cdot ha^{-1}$, and the range (2018-2019 season) was 0.011~0.114 $t \cdot ha^{-1}$. The values of NRMSE (2017-2018 season) ranged from 0.456% to 1.544%, and the values (2018-2019 season) ranged from 0.084% to 0.793%. The absolute CRM values were all less than 1.5%, RMSE values were less than 0.25 $t \cdot ha^{-1}$, and NRMSE values were less than 2.0%, which indicated that the precise of biomass simulation was high.

The CRM range of winter wheat (2017-2018 season) yield simulation values was -1.204%~-0.307%, and the range of the CRM (2018-2019 season) was -1.055%~0.369% under the measured CO_2 database in Table 7. The values of the RMSE ranged from 0.050~0.078 $t \cdot ha^{-1}$ (2017-2018 season), and the range (2018-2019 season) was 0.048~0.130 $t \cdot ha^{-1}$. The values of the NRMSE (2017-2018 season) ranged from 0.843%~1.304%, and the range (2018-2019 season) was 0.679%~1.932%. The absolute CRM values were all less than 1.5%, the RMSE values were less than 0.15 $t \cdot ha^{-1}$, and

274 the NRMSE values were less than 2.0%, which indicated that the precise of yield
275 simulation was high.

276 As can be seen from Fig.3 and Fig.4, the R^2 of biomass under different CO_2
277 databases for different irrigation levels of winter wheat were 0.992 and 0.967,
278 respectively. And the R^2 of the yield were 0.974 and 0.857, respectively. The accuracy
279 of the biomass and yield simulation under the default and measured CO_2 database were
280 both good. Compared with the default CO_2 database, the simulation accuracy of winter
281 wheat yield and biomass under the measured CO_2 database was higher. So, the
282 measured CO_2 database can improve the model simulation accuracy.

283 The water use efficiency of winter wheat in the 2018-2019 season under the
284 measured CO_2 database, were 1.63kg/m³, 1.72 kg/m³and 1.56 kg/m³, respectively,
285 under the three irrigation levels. The water use efficiency under the default CO_2
286 database were 1.66 kg/m³, 1.71 kg/m³ and 1.54 kg/m³, respectively. The water use
287 efficiency under the two CO_2 databases is the highest when the irrigation level is T2,
288 which is consistent with the research conclusion (Xing et al., 2016).

289 *Impact analysis of parameters under different CO_2 databases*

290 The calibration parameters of the AquaCrop under two different CO_2 databases
291 were shown in Table 8. The calibration parameters included the length building up HI,
292 the maximum root depth, water productivity and crop growth temperature. According
293 to formulas 4-6, the values in parentheses are the adjusted values of WP*. When the

294 default CO_2 database was used in the model, there was a little influence on the
295 calibration parameters of the model.

296 **4 Validation of the AquaCrop model under the measured CO_2 database**

297 4.1 Validation analysis of field evapotranspiration

298 The ET_a (actual evapotranspiration), called measured evapotranspiration, can be
299 calculated according to the water balance method by using the data of rainfall and soil
300 water content. The water balance equation is as follows:

301 $$ET_a = W_0 - W_t + P + I + K - R - D \quad (12)$$

302 Where ET_a is the crop evapotranspiration (mm); W_0 and W_t are the soil water storage
303 at the beginning and the end of the calculation period (mm); P is the precipitation (mm);
304 I is the amount of irrigation water (mm); K is the amount of groundwater recharge to
305 the upper layer, because the groundwater is buried deep in the study area, the amount
306 of groundwater recharge can be ignored (mm); R is the surface runoff (mm); D is the
307 deep leakage (mm). Because the amount of rainfall (or irrigation) is relatively small
308 and the land is relatively flat, surface runoff and deep leakage can be ignored.

309 It can be seen from Fig.5 that the change process of measured and simulated
310 evapotranspiration was consistent under different irrigation levels. The field
311 evapotranspiration was close to the measured value in the seedling, overwintering and
312 mature period. During the filling and waxing period of winter wheat, due to the
313 combined effect of rainfall and irrigation, there were some errors between the measured

values and the values of simulation. In general, the simulation values of field evapotranspiration were consistent with the measured values of winter wheat (2018-2019 season) under different irrigation levels.

The evapotranspiration of winter wheat was dominated by field soil evaporation before and after seedling stage. The main reason was that the crop plants were small and the bare soil was dominant in the field. So, the transpiration of the crop was smaller than the soil evaporation. With the development of seedlings and the decrease of air temperature, the evaporation capacity of field soil weakened. Field evapotranspiration, soil evaporation and crop transpiration of winter wheat in overwintering period were very small. When winter wheat was in the jointing stage, the plants grew and developed rapidly as the temperature raised and the canopy of winter wheat expanded rapidly, too. The transpiration of crops started to increase while the evaporation of soil started to decrease. The transpiration of winter wheat gradually reached the maximum value from the filling stage to the waxing stage. The field evapotranspiration and crop transpiration began to decrease, concurrently, the soil evaporation began to increase at the mature period of winter wheat.

4.2 Validation analysis of soil water content

The main factors affecting soil water storage were precipitation, ambient temperature, field irrigation, and crop water consumption during the growth and development of winter wheat. AquaCrop model is a water-driven model, so the crop

334 water consumption during the crop growth period determined the simulation precision
335 of crop biomass and yield. And the crop water consumption was mainly provided by
336 soil water content. Therefore, the performance of the AquaCrop model was determined
337 by the dynamic change of soil water content (Ahmadi et al. 2015). The process of soil
338 water content change (within the effective root depth of 0-140cm) in the test plots
339 during the growth period of winter wheat in 2018-2019 season were shown in Figure 6.
340 The errors between the simulated and the measured values of soil water content at
341 the irrigation amount (T1) and (T3) were large, while the errors under appropriate
342 irrigation amount (T2) was small in Figure 6. The reason might be that the smaller
343 irrigation amount (T3) had more severe effect on the growth of winter wheat by water
344 stress, which led to an increase demand for soil moisture during the growth of winter
345 wheat, resulting in a large deviation between the actual measured soil water content and
346 the simulated value. The larger irrigation amount (T1) may lead to deep leakage of soil
347 water, resulting in a large deviation between the simulated value and the measured value.
348 In addition, the simulation accuracy of the larger irrigation amount (T1) was higher
349 than that of the lower irrigation amount (T3). The reason might be that when the soil
350 was replenished with a large amount of irrigation, the soil can store redundant water to
351 meet the growth of the crop. When the amount of irrigation was small, soil moisture
352 cannot be replenished, and the impact of water stress on crop growth was increasing.
353 The simulated values of the AquaCrop model for soil water content at the three levels
354 of irrigation were all higher than the measured values. The deviation of the simulation

355 results might be caused by the differences of the soil structure and texture in the test
356 plots. At the same time, the failure of the AquaCrop model to take into account the
357 variability of soil texture and structure in the soil module was also the reason for the
358 deviation of the simulated values from the actual measured values. Overall, the
359 simulated values for soil water storage were larger than the measured values, but the
360 simulated results largely reflected the dynamic changes in soil water content throughout
361 the growth period of winter wheat.

362 **5 Conclusions**

363 (1) The AquaCrop model has been proven to simulate the biomass and yield of
364 winter wheat with good accuracy in North China Plain. However, the default CO_2
365 database was adopted in the simulation, which may affect the simulation results. To
366 examine whether the use of default CO_2 database affected the simulation results, this
367 paper built the AquaCrop models based on the measured CO_2 database and the default
368 CO_2 database, respectively. The results showed that the accuracy of the biomass and
369 yield simulation under the default and measured CO_2 database were all good, but the
370 latter has higher simulation accuracy.

371 (2) The difference between crop transpiration and soil evaporation under the two
372 CO_2 databases was not obvious, and the measured value was close to the field
373 evapotranspiration in the seedling, overwintering and mature period. During the filling
374 and waxing period of winter wheat, there were some errors between the measured

values of field evapotranspiration and the values of simulation. In general, the simulation values of field evapotranspiration were consistent with the measured values of winter wheat at different irrigation levels.

(3) The simulated values of the AquaCrop model for soil water content at the three levels of irrigation were all higher than the measured values. The errors between the simulated and the measured values of soil water content at the irrigation amount (T1) and (T3) were larger than that of the irrigation amount (T2). Overall, the simulated values for soil water storage were larger than the measured values, but the simulated results largely reflected the dynamic changes in soil water content throughout the growth period of winter wheat.

Declarations

Data Availability

The datasets used during the current study are available from the corresponding author on reasonable request.

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Contributions

All authors were involved in the production and writing of the manuscript. Methodology, F.L. and C.S.; Formal Analysis, F.L. and C.S.; Data Curation, H.L.; Review & Editing, F.L. and C.S.; All authors have read and agreed to the published version of the manuscript.

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Compliance with Ethical Standards

Conflicts of interest/Competing interests

The authors declare that they have no competing interests.

Consent to Participate

The authors declare that they consent to participate.

Consent for Publication

The authors declare that they consent to publish.

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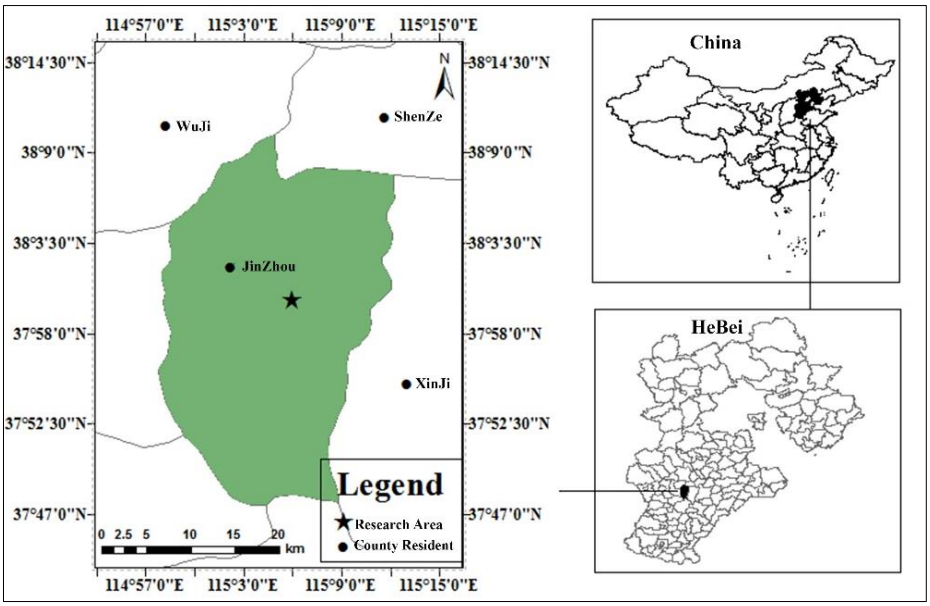

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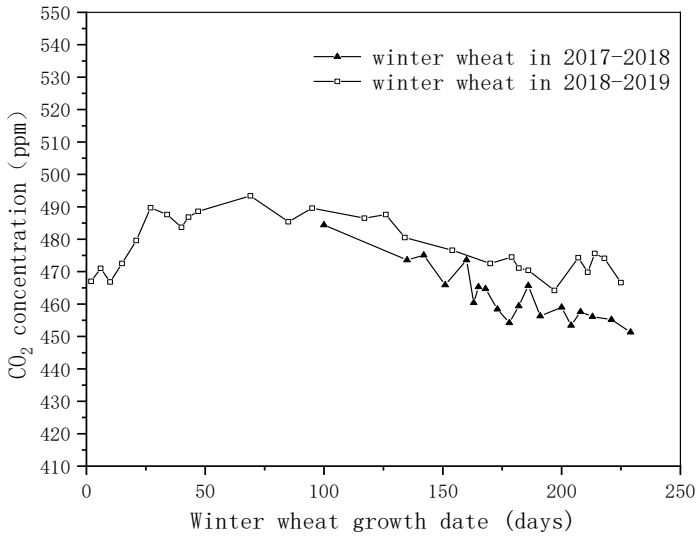
516 Fig.1 The location of study area



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518 Fig.2 Variation curve of atmospheric CO_2 concentration in 2017-2019

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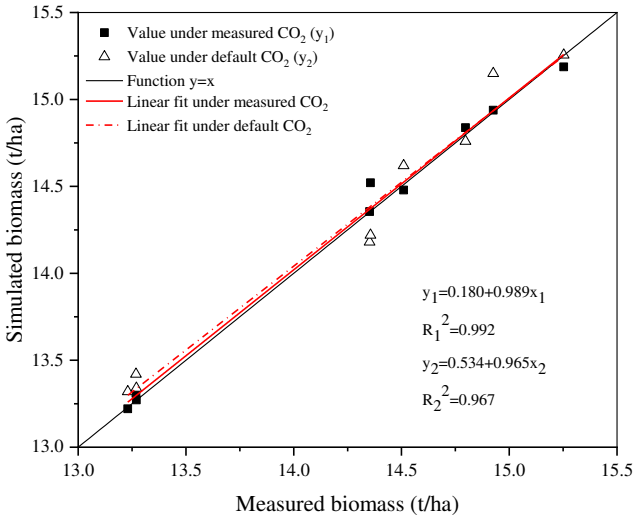

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522 Figure 3. Linear fitted relationship between measured and simulated values of biomass

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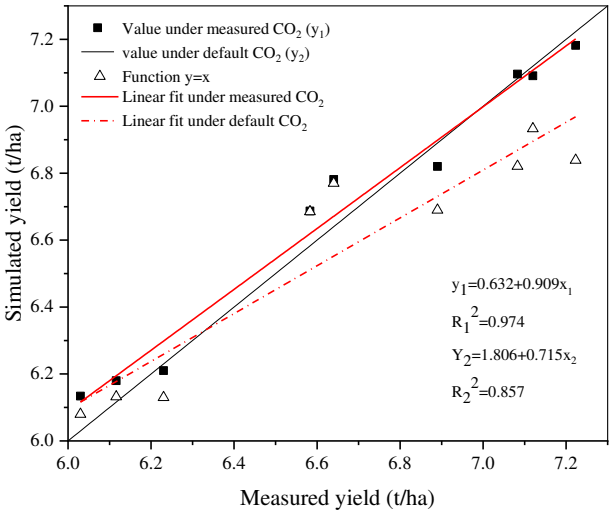

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525 Figure 4. Linear fitting relationship between measured and simulated values of yield

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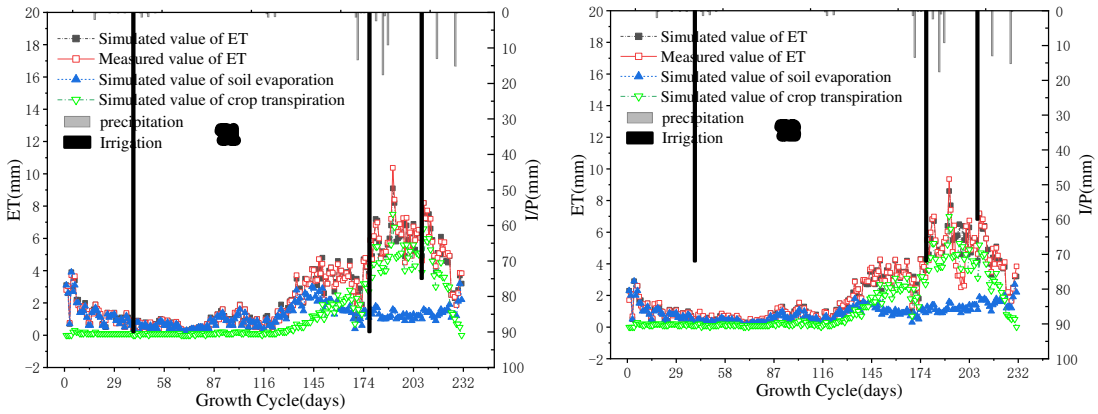

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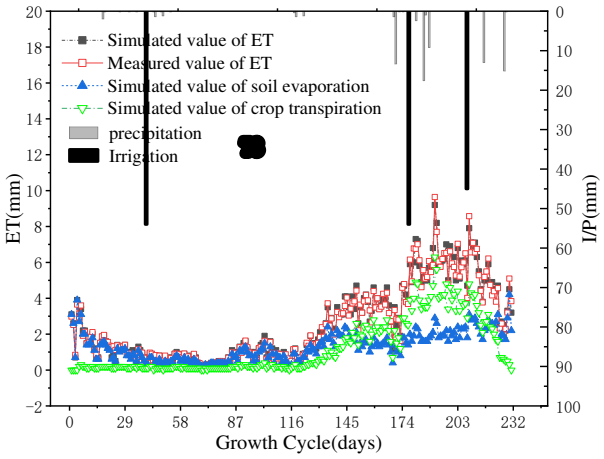

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530 Figure 5. The process of field evapotranspiration under different irrigation levels

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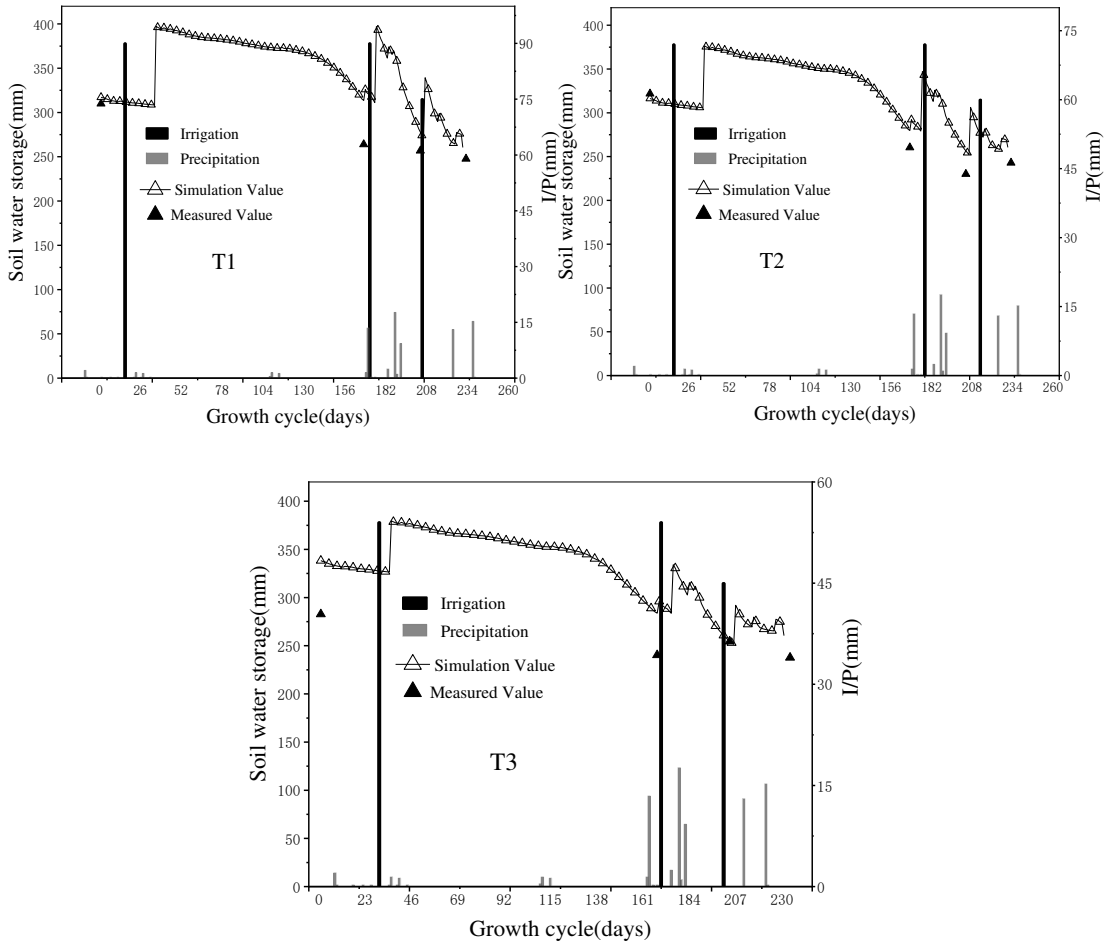

Figure 6. Curves of soil moisture content change under different experimental treatments

Table 1. 2017-2019 winter wheat irrigation scheme

Irrigation date	Net irrigation amount（mm）						
	2017-2018			Irrigation date	2018-2019		
	T1	T2	T3		T1	T2	T3
12.11（10.25）	60	50	40	11.27（10.23）	90	72	54
4.2	60	50	40	4.16	90	72	54
5.13	60	50	40	5.17	75	60	45

544 Table 2. Soil parameters of study area

Soil parameters	Thickness (cm)					
	0-20	20-40	40-60	60-80	80-100	100-120
Silt content/%	92.04	88.37	90.66	60.32	58.60	57.36
Clay content/%	3.30	4.73	4.46	30.88	31.45	31.88
Sand content/%	4.65	6.90	4.88	8.80	9.95	10.76
Permanent wilting point/$m^3 \cdot m^{-3}$	10.6	10.8	11.3	13.6	13.6	14.3
Soil bulk density /$g \cdot cm^{-3}$	1.21	1.23	1.29	1.38	1.47	1.45
Water content at saturation （weight）/%	42.14	42.63	42.56	46.05	47.17	47.25
Field capacity（weight）/%	32.79	32.58	32.57	33.02	38.84	38.85

545 Table 3. Conservative parameters of AquaCrop model

Describe	Value	Unit
Soil surface covered by an individual seedling at 90% emergence	1.5	cm^2
Base temperature	0.0	℃
Upper temperature	26.0	℃
Crop determinacy linked with flowering	YES	-
Effect of canopy cover in reducing soil evaporation in late season stage	1.5	-
Effect of canopy cover in reducing soil evaporation in late season stage	50	-
Allowable maximum increase (%) of specified HI	15	%
Minimum air temperature below which pollination starts to fail (cold stress)	5	℃
Maximum air temperature above which pollination starts to fail (heat stress)	35	℃
Water productivity normalized for ET0 and CO_2	15.0	$g \cdot m^{-2}$

546

547 Table 4. Biomass of winter wheat at different irrigation levels (Maunaloa.CO_2)

Planting season	Irrigation level	Biomass（mean）				
		Simulated ($t \cdot ha^{-1}$)	Measured ($t \cdot ha^{-1}$)	CRM (%)	RMSE($t \cdot ha^{-1}$)	NRMSE (%)
2017-2018	T1	13.372	13.214	-1.193	0.257	1.948
	T2	12.790	13.030	1.844	0.216	1.654
	T3	12.259	12.390	1.063	0.037	0.298
2018-2019	T1	15.028	15.028	-0.004	0.130	0.864
	T2	14.284	14.418	0.932	0.299	2.076
	T3	13.357	13.268	-0.676	0.130	0.981

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549

550 Table 5. Yield of winter wheat at different irrigation levels (Maunaloa.CO_2)

Planting season	Irrigation level	Grain yield（mean）				
		Simulated ($t \cdot ha^{-1}$)	Measured ($t \cdot ha^{-1}$)	CRM (%)	RMSE($t \cdot ha^{-1}$)	NRMSE (%)
2017-2018	T1	6.126	6.119	-0.104	0.142	2.327
	T2	5.974	5.970	-0.073	0.037	0.628
	T3	5.641	5.610	-0.559	0.025	0.447
2018-2019	T1	6.921	7.139	3.049	0.238	3.327
	T2	6.733	6.729	-0.059	0.182	2.699
	T3	6.087	6.106	0.311	0.045	0.741

551

552 Table 6. Biomass of winter wheat at different irrigation levels (measured CO_2)

Planting season	Irrigation level	Biomass（mean）				
		Simulated ($t \cdot ha^{-1}$)	Measured ($t \cdot ha^{-1}$)	CRM (%)	RMSE($t \cdot ha^{-1}$)	NRMSE (%)
2017-2018	T1	13.310	13.214	-0.727	0.204	1.544
	T2	12.968	13.030	0.478	0.099	0.761
	T3	12.248	12.390	1.151	0.057	0.456
2018-2019	T1	15.013	15.028	0.100	0.093	0.616
	T2	14.458	14.418	-0.273	0.114	0.793
	T3	13.270	13.268	-0.020	0.011	0.084

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554

555 Table 7. Winter wheat yield at different irrigation levels (measured CO_2)

Planting season	Irrigation level	Grain yield（mean）				
		Simulated ($t \cdot ha^{-1}$)	Measured ($t \cdot ha^{-1}$)	CRM (%)	RMSE($t \cdot ha^{-1}$)	NRMSE (%)
2017-2018	T1	6.193	6.119	-1.204	0.078	1.276
	T2	5.988	5.970	-0.307	0.050	0.843
	T3	5.639	5.610	-0.523	0.073	1.304
2018-2019	T1	7.113	7.139	0.369	0.048	0.679
	T2	6.800	6.729	-1.055	0.130	1.932
	T3	6.153	6.106	-0.759	0.064	1.049

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557

558 Table 8. Calibration of some parameters of AquaCrop model under two CO_2 databases

Model parameters	Default CO_2	Measured CO_2
Planting to maturity(days)	230	230
Maximum rooting depth (m)	1.40	1.40
Harvest index (%)	46	46
Plant density (plants $\cdot m^{-2}$)	318.75	318.75
Water productivity normalized for ET_0 and CO_2 ($g \cdot m^{-2}$)	15（15.9）	15（17.2）
Length building up HI (days)	34	34
Planting to flowering(days)	191	191
Planting to maximum canopy cover(days)	196	196
Maximum canopy cover (%)	96	96
Base temperature (℃)	0	0
Upper temperature (℃)	26	26

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