agriculture

MDPI

Article

Assessing Growth and Water Productivity for Drip-Irrigated Maize under High Plant Density in Arid to Semi-Humid Climates

Feng Wang [1,2], Jun Xue [1], Ruizhi Xie [1], Bo Ming [1], Keru Wang [1], Peng Hou [1], Lizhen Zhang [3,*] and Shaokun Li [1,*]

1 Institute of Crop Sciences, Chinese Academy of Agricultural Sciences/Key Laboratory of Crop Physiology and Ecology, Ministry of Agriculture and Rural Affairs, Beijing 100081, China; wangfen@gsau.edu.cn (F.W.); xuejun@caas.cn (J.X.); xieruizhi@caas.cn (R.X.); mingbo@caas.cn (B.M.); wangkeru@caas.cn (K.W.); houpeng@caas.cn (P.H.)

2 Gansu Provincial Key Laboratory of Aridland Crop Sciences, College of Agronomy, Gansu Agricultural University, Lanzhou 730070, China

3 College of Resources and Environmental Sciences, China Agricultural University, Beijing 100193, China

* Correspondence: Zhanglizhen@cau.edu.cn (L.Z.); lishaokun@caas.cn (S.L.)

Abstract: Determining the water productivity of maize is of great significance for ensuring food security and coping with climate change. In 2018 and 2019, we conducted field trials in arid areas (Changji), semi-arid areas (Qitai) and semi-humid areas (Xinyuan). The hybrid XY335 was selected for the experiment, the planting density was 12.0×10^4 plants ha^{-1}, and five irrigation amounts were set. The results showed that yield, biomass, and transpiration varied substantially and significantly between experimental sites, irrigation and years. Likewise, water use efficiency (WUE) for both biomass (WUE_B) and yield (WUE_Y) were affected by these factors, including a significant interaction. Normalized water productivity (WP*) of maize increased significantly with an increase in irrigation. The WP* for film mulched drip irrigation maize was 37.81 g m^{-2} d^{-1}; it was varied significantly between sites and irrigation or their interaction. We conclude that WP* differs from the conventional parameter for water productivity but is a useful parameter for assessing the attainable rate of film-mulched drip irrigation maize growth and yield in arid areas, semi-arid areas and semi-humid areas. The parametric AquaCrop model was not accurate in simulating soil water under film mulching. However, it was suitable for the prediction of canopy coverage (CC) for most irrigation treatments.

Keywords: AquaCrop model; normalized water productivity; film-mulched drip irrigation; dense planting; multi-ecological area

Citation: Wang, F.; Xue, J.; Xie, R.; Ming, B.; Wang, K.; Hou, P.; Zhang, L.; Li, S. Assessing Growth and Water Productivity for Drip-Irrigated Maize under High Plant Density in Arid to Semi-Humid Climates. *Agriculture* **2022**, *12*, 97. https://doi.org/10.3390/agriculture12010097

Academic Editor: Gerard Arbat

Received: 4 December 2021
Accepted: 8 January 2022
Published: 11 January 2022

1. Introduction

Irrigation in agriculture mainly uses fresh water, which accounts for more than 70% of the total amount in the world [1,2]. Water shortage is a main factor limiting crop growth and grain yield in arid and semi-arid agricultural areas [3–5]. The most effective way to reduce agricultural water use is by reducing the planting of water-consuming crops. However, it was predicted by the Food and Agriculture Organization (FAO) that global food production needs to increase by 70% to meet the needs of an additional 2.3 billion people by 2050 [6]. The AquaCrop model developed by FAO could predict crop productivity, water demand and water use efficiency under limited water conditions in 2009 [7,8]. At present, AquaCrop has been proven to be an effective tool to simulate the response of maize yield to an irrigation system and soil moisture conditions [9–14]. In addition, the model has also been successfully applied to the research of other crops, such as wheat [15–17], rice [18] and cotton [19–21]. In China, predecessors evaluated the applicability of AquaCrop model in maize [22,23], wheat [24,25], rice [26] and other crops. However, these studies mainly focused on areas with relatively more rainfall in northeast, north and central China. There are few studies in the inland areas of northwest China, with drought, high temperature and less rainfall.

Film-mulched drip irrigation is a new agricultural water-saving technology that combines plastic film mulching with a drip irrigation system. It increases soil temperature, reduces soil evaporation and water loss [27,28], and improves crop yield and water use efficiency [29,30]. At present, this technology is widely used in the production of field crops in northwest China [31–33]. Many attempts have been made to use the AquaCrop model in film mulch. Liu et al. (2015) and Yang et al. (2015) suggested quantifying the relationship between soil-accumulated and air-accumulated temperatures under the film mulch [22,23]. The air-accumulated temperature parameters corresponding to the soil-accumulated temperature were input into the model. As it is known, the AquaCrop model contains the setting of ground cover parameters. In order to realize the simulation of seed maize production under film mulch, Ran et al. (2018) calibrated crop parameters by actually observing the response of yield formation [13]. However, the feasibility of this method needs to be verified under film-mulched drip irrigation and dense planting modes.

In addition, normalized water productivity, WP* (g m^{-2} d^{-1}), was defined as the ratio between crop biomass and the integral of normalized daily transpiration over the growth duration of the crop [34]. AquaCrop uses WP* to estimate the attainable rate of crop growth under water limitation. WP* was not sensitive to changes in soil nutrient status and may only slightly change under different climates [34]. In a word, WP* is a conservative value. There are few studies on values of WP*, however, and no reports for drip maize under plastic film mulching and closed planting in arid to semi-humid areas. It is not clear whether the default parameters provided by the model and the parameters calibrated by predecessors under plastic film mulching can be used directly. Therefore, the purpose of this study is to parameterize the AquaCrop model of maize under the mode of drip irrigation under plastic film and closed planting to simulate the growth of maize. Second, we assume that maize productivity may be different under different irrigation amounts and verify this hypothesis by actually measuring the biomass and calculating the water productivity of different irrigation amounts.

2. Materials and Methods

2.1. Site Description

Field experiments were conducted in 2018 and 2019 at the Experimental Station of the Western Agricultural Research Center of the Chinese Academy of Agricultural Sciences (Changji, 44°9′33″ N, 87°11′59″ E, 470 m a.s.l.), Qitai Farm (Qitai, 43°29′15″ N, 89°28′42″ E, 1021 m a.s.l.), and Xinyuan Farm (Xinyuan, 43°27′37″ N, 83°19′50″ E, 817 m a.s.l.) (Figure 1). Changji, Qitai and Xinyuan represent arid, semi-arid, and semi-humid climates, respectively [35]. Every year, plant growth was monitored from sowing to harvesting of maize. The data of weather, initial soil water content and development stage of the entire season were collected. The above data were used as input in the AquaCrop model. The model was then used to calculate the difference between normalized water productivity and water use efficiency. The results of the model were verified by comparing simulated canopy coverage with canopy cover estimated based on field measured leaf area index, simulated biomass and measured biomass, simulated soil water storage and observed soil water storage. The experimental results and calculated WUE_B and WP* were statistically analyzed to evaluate the variability among different ecological regions.

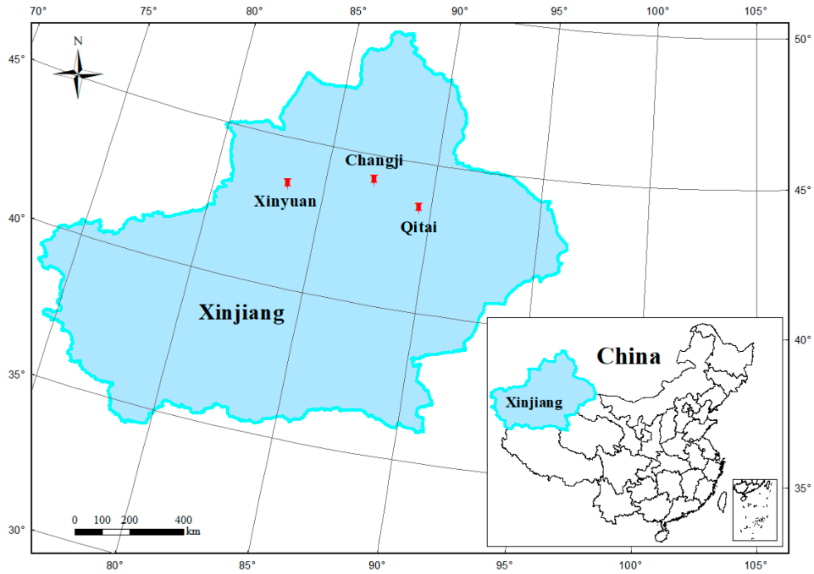

Figure 1. Location of experimental sites in Xinjiang.

2.2. Experimental Design and Field Management

A high-yield maize hybrid Xianyu 335 was used. Its planting density was 12.0×10^4 ha^{-1} in the three experimental sites. Drip irrigation under plastic film mulching was used and each treatment and was repeated 3 times. The area of each plot was 165 m^2 (length–15 m, width–11 m). The plants were sown with alternating wide and narrow rows of 70 and 40 cm, respectively.

The local farmers' conventional irrigation amount was taken as the maximum irrigation amount (I5), and the 90 mm was reduced successively for the set irrigation treatment. Five irrigation quantities were set up in Changji, Qitai and Xinyuan in 2018. I1 (450 mm), I2 (540 mm), I3 (630 mm), I4 (720 mm), and I5 (810 mm) at Changji; I1 (360 mm), I2 (450 mm), I3 (540 mm), I4 (630 mm), and I5 (720 mm) at Qitai; I1 (180 mm), I2 (270 mm), I3 (360 mm), I4 (450 mm), and I5 (540 mm) at Xinyuan in 2018; and I1 (0 mm), I2 (180 mm), I3 (270 mm), I4 (360 mm), and I5 (450 mm) at Xinyuan in 2019. The specific experimental design was shown in Table 1. After sowing, all experimental fields were immediately irrigated with water according to soil water storage at topsoil (0–20 cm) to guarantee the uniform and rapid germination of seeds. Each district has a separate water meter to accurately measure and control the amount of irrigation water.

Table 1. Irrigation schedule applied at the Changji, Qitai, and Xinyuan farms in 2018 and 2019.

Site	Year	Total Irrigation Amount (mm)	SWS (0–20 cm) before Sowing (mm)	Irrigation Amount 3 Days after Sowing (mm)	Irrigation Interval in Growth Period (d)	Irrigation Times in Growth Period
Changji	2018	I1(450), I2(540), I3(630), I4(720), I5(810)	29.9	45	8–9	9
	2019	I1(450), I2(540), I3(630), I4(720), I5(810)	33.4	40	8–9	9
Qitai	2018	I1(360), I2(450), I3(540), I4(630), I5(720)	46.7	30	8–9	9
	2019	I1(360), I2(450), I3(540), I4(630), I5(720)	50.7	30	8–9	9

Table 1. *Cont.*

Site	Year	Total Irrigation Amount (mm)	SWS (0–20 cm) before Sowing (mm)	Irrigation Amount 3 Days after Sowing (mm)	Irrigation Interval in Growth Period (d)	Irrigation Times in Growth Period
Xinyuan	2018	I1(90), I2(180), I3(270), I4(360), I5(450)	55.5	30	12–15	4
	2019	I1(0), I2(90), I3(180), I4(270), I5(360)	62.8	0	12–15	3

Note: SWS, soil water storage (mm); VE, emergence of seedlings. The first irrigations were on 16 June 2018 and 11 June 2019 in Changji, 25 June 2018 and 26 June 2019 in Qitai, and 5 July 2018 and 8 July 2019 in Xinyuan.

2.3. AquaCrop Model Input Elements

According to the input requirements of the AquaCrop model, parameter databases of meteorology, crops, soil and management were established.

2.3.1. Meteorological Data

Daily weather data of rainfall, wind speed, minimum and maximum temperature, sunshine hours and relative humidity were obtained from a standard weather station at experimental sites. The daily rainfall and maximum and minimum temperatures are shown in Figure 2. The ET_0 was based on the FAO Penman–Monteith equation [36].

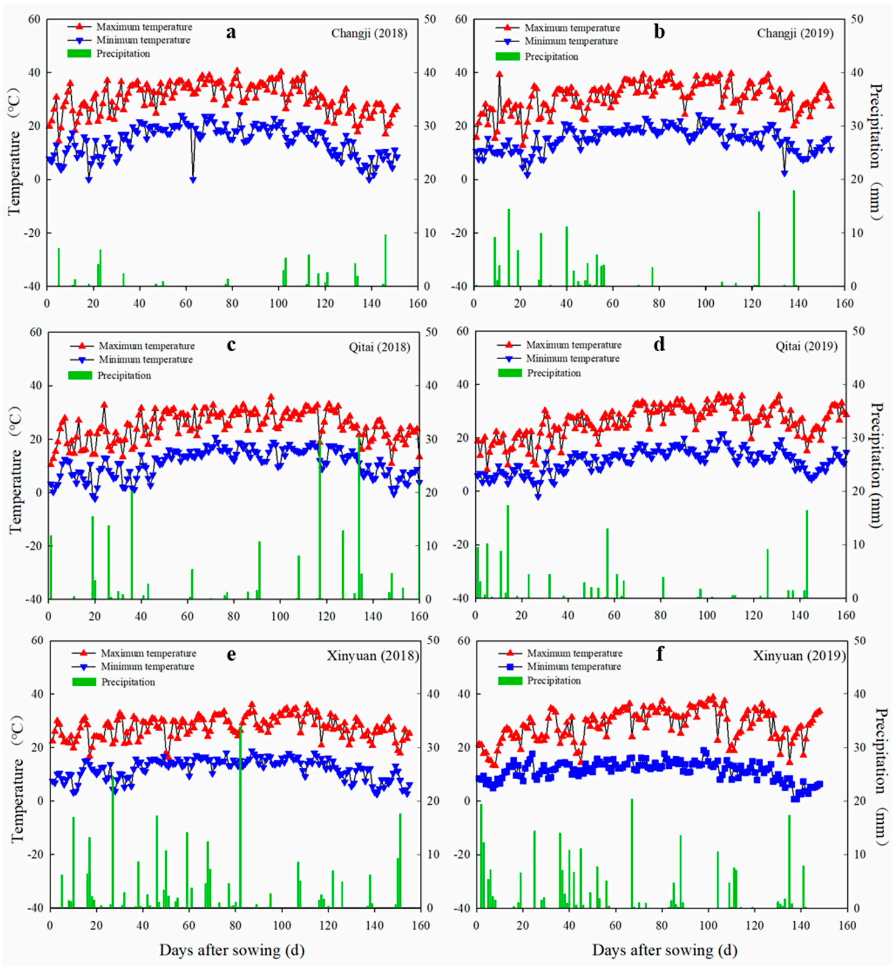

Figure 2. Daily rainfall and maximum and minimum temperatures at Changji, Qitai and Xinyuan (over maize–cropping season) in 2018 and 2019. Note: (**a**) Changji 2018, (**b**) Changji 2019, (**c**) Qitai 2018, (**d**) Qitai 2019, (**e**) Xinyuan 2018, and (**f**) Xinyuan 2019.

2.3.2. Soil Data

The input soil parameters required for AquaCrop were saturated hydraulic conductivity (K_{sat}), saturated volume water content (sat), field capacity and permanent wilting point (Table 2). The field capacity and permanent wilting point were field measured values, and other parameters adopted the reference values by AquaCrop. Field capacity was measured by the ring knife method. The permanent wilting point was the soil water content measured when the maize seedling entered into permanent wilting. The groundwater of Changji and Qitai was below 10 m, and that of Xinyuan was about 2.5 m.

Table 2. Soil properties (0–100 cm) for experiments conducted in station.

Site	Texture	Water Content at Saturation	Field Capacity	Permanent Wilting Point	K_{sat}
			m^3 m^{-3}		mm d^{-1}
Changji	loamy sand	0.32	0.16	0.09	1950.00
Qitai	sandy loam	0.41	0.28	0.12	850.00
Xinyuan	silt loam	0.46	0.33	0.13	575.00

2.3.3. Crop Data

The dates of maize sowing, emergence, maximum canopy cover, flowering, canopy decay and harvest were accurately recorded in 2018 and 2019.

Canopy coverage (CC): five representative plants were randomly sampled at the V6, V12, R1, R3, R4, R5 and R6 stages. The length and width of each green leaf were measured in the above-growth stage. The leaf area per plant (LA) of each plant was calculated according to length × width × 0.75 (expanded leaves) and length × width × 0.5 (unexpanded leaves). The leaf area index (LAI) refers to the land area occupied by the LA × the number of plants per unit area. The corresponding canopy coverage was calculated according to Equation (1) [9].

$$CC = 1.005 \times [1 - exp(-0.6LAI)]^{1.2} \quad (1)$$

Root depth: the maximum effective root depth of maize measured in Changji, Qitai and Xinyuan was 0.6 m.

Biomass: the five maize plants were dried at 105 °C for 30 min and dried at 85 °C and then weighed to obtain aboveground biomass.

Yield: artificial harvest was carried out at physiological maturity. Maize plants in an area of 66 m^2 from the middle six rows of each plot were harvested manually. According to the average panicle weight method, 20 ears were collected as standard samples per plot.

2.3.4. Manage Data

Management data included irrigation measures and field management. Drip irrigation was chosen as the irrigation method. The mulch was plastic, and its proportion was 40%. The dense planting (12.0×10^4 ha^{-1}) was set. The sowing dates were 3 May and 25 April in Changji, 19 and 21 April in Qitai, and 28 and 28 April in Xinyuan, the harvest dates were 5 October and 26 September, 10 and 3 October, and 30 and 23 September in 2018 and 2019, respectively. In order to promote the deeper penetration of maize roots to prevent lodging (which occurred mainly in stages VT–R3), no irrigation was applied between certain stages to induce slight drought, these stages were from VE (emergence) to V6 in Changji, from VE to V10 in Qitai, and from VE to V12 in Xinyuan. Fertilization was provided in sufficient quantities to ensure that nutrients were not restricted during maize growth. All weeds, diseases and insect pests were effectively controlled.

2.4. AquaCrop Model Run

The Aqua Crop model provided a series of maize parameters, some of which had been proven or assumed to be conservative (constant) in the research [9]. In this study, most of the parameters refer to the values provided by Hsiao et al. (2009) (Table 3). The remaining parameters were calibrated according to the corresponding test data (Table 4).

Table 3. Default parameters of maize in AquaCrop in Changji, Qitai and Xinyuan from 2018 to 2019.

Description	Default Value
Base temperature, °C	8.0
Upper temperature, °C	30
Canopy size of the average seedling at 90% emergence(CC_0), cm^2	6.5
Minimum effective rooting depth, m	0.3
Canopy growth coefficient (CGC),%	1.3
Leaf growth threshold (p_{upper})	0.14
Leaf growth threshold (p_{lower})	0.72
Leaf growth stress coefficient curve shape	2.9
Stomatal conductance threshold (p_{upper})	0.69
Stomata stress coefficient curve shape	6.0
Senescence stress coefficient (p_{upper})	0.69
Senescence stress coefficient curve shape	2.7
Allowable maximum increase in specified HI	15
Coefficient, inhibition of leaf growth on HI	7.0
Coefficient, inhibition of stomata on HI	3.0

Table 4. Calibrated values of parameters in the AquaCrop model from 2018 to 2019.

Site	**Description**	**Calibrated Value**				
		I1	**I2**	**I3**	**I4**	**I5**
Changji	GDD from sowing to 90% emergence (CC_0)	67/72	67/72	67/72	67/72	67/72
	GDD from sowing to maximum canopy coverage	822/766	822/766	805/750	798/750	798/750
	GDD from sowing to start of anthesis	1165/1031	1165/1031	1152/1015	1116/1000	1116/1000
	Duration of anthesis, in GDD	246/243	250/243	242/243	242/244	242/244
	GDD sowing-canopy senescence	1702/1638	1754/1653	1763/1668	1763/1698	1763/1698
	GDD from sowing to maximum root depth	1516/1378	1500/1361	1472/1344	1446/1325	1446/1325
	GDD from sowing to maturity	2013/2088	2013/2088	2013/2088	2013/2088	2013/2088
	GDD from sowing to 90% emergence (CC_0)	67/64	67/64	67/64	67/64	67/64
Qitai	GDD from sowing to maximum canopy coverage	669/544	669/544	669/544	669/544	669/544
	GDD from sowing to start of anthesis	886/801	864/801	840/786	840/771	840/771
	Duration of anthesis, in GDD	194/209	194/209	194/209	194/209	194/209
	GDD from sowing to canopy senescence	1504/1419	1516/1419	1522/1422	1522/1422	1522/1422
	GDD from sowing to maximum root depth	1183/1110	1135/1095	1120/1079	1126/1063	1120/1063
	GDD from sowing to maturity	1626/1687	1626/1687	1626/1687	1626/1687	1626/1687
Xinyuan	GDD from sowing to 90% emergence (CC_0)	70/62	70/62	70/62	70/62	70/62
	GDD from sowing to maximum canopy coverage	634/626	634/626	634/626	634/626	634/626
	GDD from sowing to start of anthesis	885/816	872/816	872/816	872/816	872/816
	Duration of anthesis, in GDD	205/202	205/202	205/202	205/202	205/202
	GDD sowing-canopy senescence	1514/1353	1523/1353	1533/1353	1533/1353	1533/1353
	GDD from sowing to maximum root depth	1175/1088	1160/1074	1146/1060	1146/1060	1146/1060
	GDD from sowing to maturity	1774/1602	1774/1602	1774/1602	1744/1602	1774/1602
Unified calibration parameter	Maximum canopy cover, %	98				
	Reference harvest index (HI_0), %	51				
	Maximum root depth, m	0.6				
	Crop coefficient for transpiration at CC = 100% (K_cTr,x)	1.20				
	Type of surface mulches	Plastic mulches				
	Percentage of soil surface covered, %	40				

Note: GDD, growing degree day(s). The number before '/' is the GDD corresponding to 2018, and the number after it corresponds to 2019.

AquaCrop needs WP* as an input parameter to estimate biomass. In this study, however, we did not estimate the biomass of AquaCrop. We compared the biomass measured in different ecological regions with the comprehensive normalized transpiration calculated by AquaCrop to determine WP* [37]. Therefore, we only used AquaCrop's leaf growth and water balance algorithm to estimate transpiration and evaporation.

Using data of meteorological, soil, sowing date and density, and observed values during the maize growing period, the AquaCrop models were parameterized in Changji, Qitai and Xinyuan (Tables 2–4). Canopy coverage and soil water content throughout the maize season were used to test the output of AquaCrop. The calculated transpiration and field-measured dry matter were used to calculate WUE and WP*.

2.4.1. Soil Water

AquaCrop divided the soil profile into thin layers in order to accurately describe the retention, movement and absorption of water in the soil profile during the maize growing season. In this study, the soil profile was divided according to the soil compartment of 0.2 m. The maximum root depth of maize was assumed to be 0.6 m, and the soil water content and maize transpiration were calculated [8,38].

The initial soil water content (V, %) was measured by oven drying method at 0–100 cm before sowing. Time domain reflectometry (TDR, TRIME-T3, Germany) was used to measure soil water content during the maize growth period. Under the drip irrigation belt, five 150 cm long measuring tubes were arranged to measure the soil water content of 20 cm (0–100 cm) after rainfall, before irrigation and one day after irrigation.

2.4.2. Transpiration, WUE and WP*

Transpiration (Tr) was calculated with AquaCrop [38]. WUE was calculated based on the integral of the measured biomass (WUE_B, Equation (2)) or yield (WUE_Y, Equation (3)) and the actual daily transpiration calculated from sowing to harvest [37].

$$WUE_B = \frac{B}{\int_{sowing}^{harvest} Tr \cdot dt} \tag{2}$$

$$WUE_Y = \frac{Y}{\int_{sowing}^{harvest} Tr \cdot dt} \tag{3}$$

where Tr is the actual daily transpiration.

WP* was obtained by regressing the biomass sampled periodically by crops and the sum of normalized ET from emergence to each biomass sampling time [34]. The equation for calculating normalized water productivity (WP*, g m^{-2} d^{-1}) was as follows:

$$WP^* = \frac{B}{\int_{sowing}^{harvest} \frac{Tr}{ET_0} \cdot dt} \tag{4}$$

where B (g m^2) is the aboveground biomass. Tr is the actual daily transpiration, which is calculated by AquaCrop. ET_0 is the daily reference evapotranspiration. According to the Penman–Monteith Equation [36], the ET_0 was calculated based on the daily solar radiation, maximum and minimum temperature, 2 m wind speed and dew point data.

2.5. Statistical and Analysis

In our study, the soil water storage and canopy coverage of film-mulched drip maize were compared to test the applicability of the AquaCrop model. The performance of AquaCrop in predicting canopy coverage and soil water storage was evaluated by comparison of simulated results with measured data in Changji, Qitai and Xinyuan. The statistical parameters root mean square error (RMSE, Equation (5)) and the index of agreement (d, Equation (6)) were selected as indicators to analyze the fitting accuracy between the simulated values and the measured values. For the value of RMSE ≥ 0, the smaller the value, the closer the simulated value was to the measured value, and the best value was 0 [9]. d was calculated by the Willmott equation [39], and its value range is from 0 to 1. A value close to 1 indicates that the model can better simulate the researched parameters.

$$RMSE = \sqrt{\frac{1}{n}\sum_{i=1}^{n}(S_i - M_i)^2} \tag{5}$$

$$d = 1 - \frac{\sum_{i=1}^{n}(S_i - M_i)^2}{\sum_{i=1}^{n}\left(\left|S_i - \overline{M}\right| + \left|M_i - \overline{M}\right|\right)^2} \tag{6}$$

where S_i is the simulated value, M_i is the measured value, $\overline{S}$ is the simulated average value, $\overline{M}$ is the measured average value, and n is the number of samples.

Analysis of variance (ANOVA) was performed to test for yield, biomass, Tr, WUE_B, WUE_Y and WP* among irrigation treatments. Means were compared using Fisher's least significant difference (LSD) tests at $p < 0.05$ (LSD 0.05). Linear stepwise regression was conducted with SPSS software (SPSS 19.0, SPSS Institute Inc., Chicago, IL, USA) to determine the relationships between above-ground biomass and integral of actual transpiration and with integral of normalized transpiration over time for maize. In addition, the simulated (line) and calculated value (points) were conducted in the growing seasons of maize.

3. Results

3.1. Soil Water and Canopy Coverage

The soil water storage simulation and observation are shown in Figure 3. For all irrigation treatments, the parameterized AquaCrop model basically reflected the change trend of soil water. The appearance of the peak value indicated that irrigation or rainfall occurred on the day. However, the accuracy of model for simulating soil water storage was poor. The RMSE was 8.36–29.72 in Changji, 16.83–33.87 in Qitai, and 12.94–38.09 in Xinyuan. The d was 0.637–0.951 in Changji, 0.632–0.897 in Qitai, and 0.560–0.928 in Xinyuan.

Maize canopy coverage was simulated by the parametric AquaCrop model in Changji, Qitai and Xinyuan (Figure 4). In Changji, the canopy growth and maximum canopy coverage were simulated with poor accuracy at the early stage of maize. Maximum canopy coverage was underestimated. The RMSE was 10.04–24.66, and the d was 0.893–0.982. Canopy coverage of maize growing period was accurately simulated in Qitai. The RMSE was 6.85–10.21, and the d was 0.982–0.992. Compared with Changji and Qitai, the canopy coverage of Xinyuan obtained the most accurate simulation. The RMSE was 1.57–10.72, and the d was 0.978–1.000.

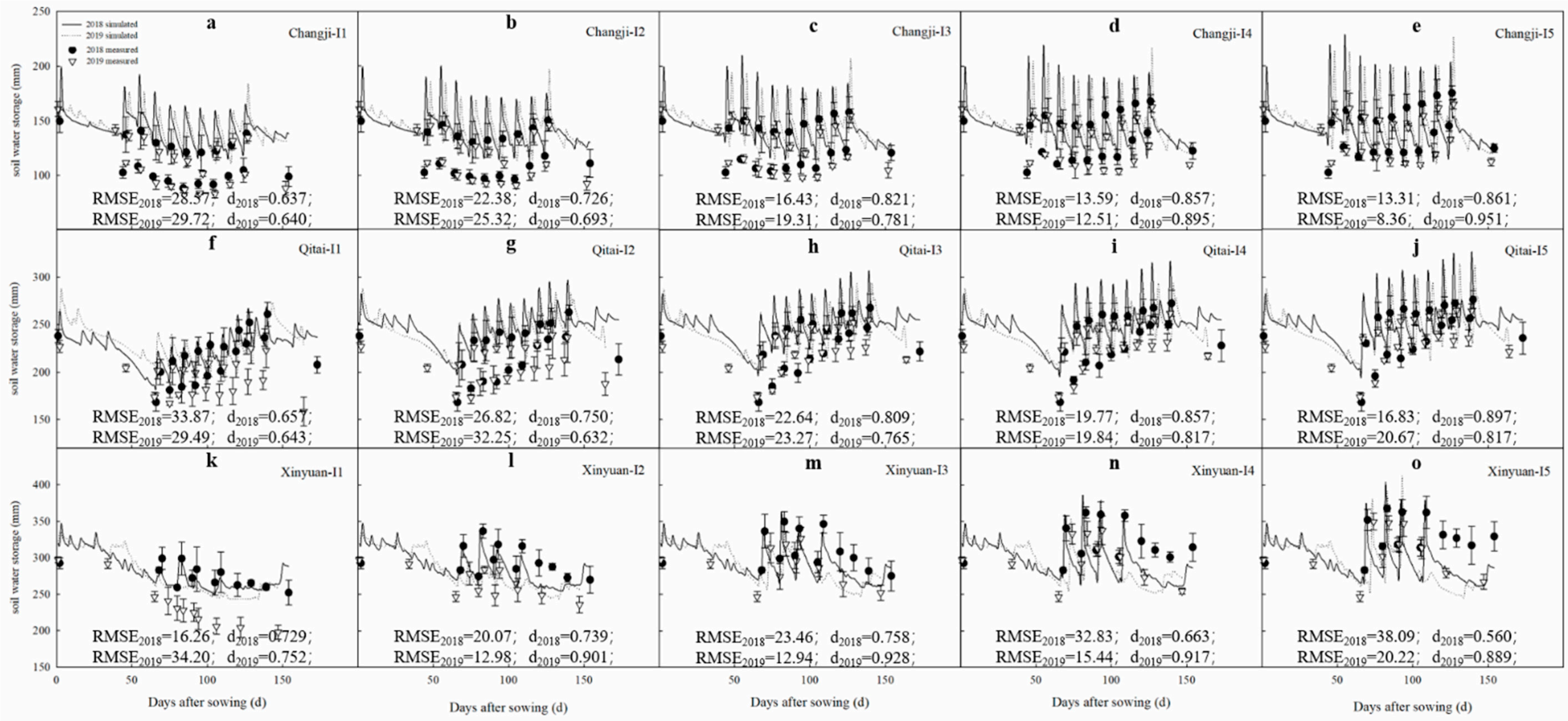

Figure 3. Simulated (line) and calculated soil water storage (points) in the growing seasons of maize. Note: (**a**) Changji I1, (**b**) Changji I2, (**c**) Changji I3, (**d**) Changji I4, (**e**) Changji I5, (**f**) Qitai I1, (**g**) Qitai I2, (**h**) Qitai I3, (**i**) Qitai I4, (**j**) Qitai I5, (**k**) Xinyuan I1, (**l**) Xinyuan I2, (**m**) Xinyuan I3, (**n**) Xinyuan I4, and (**o**) Xinyuan I5.

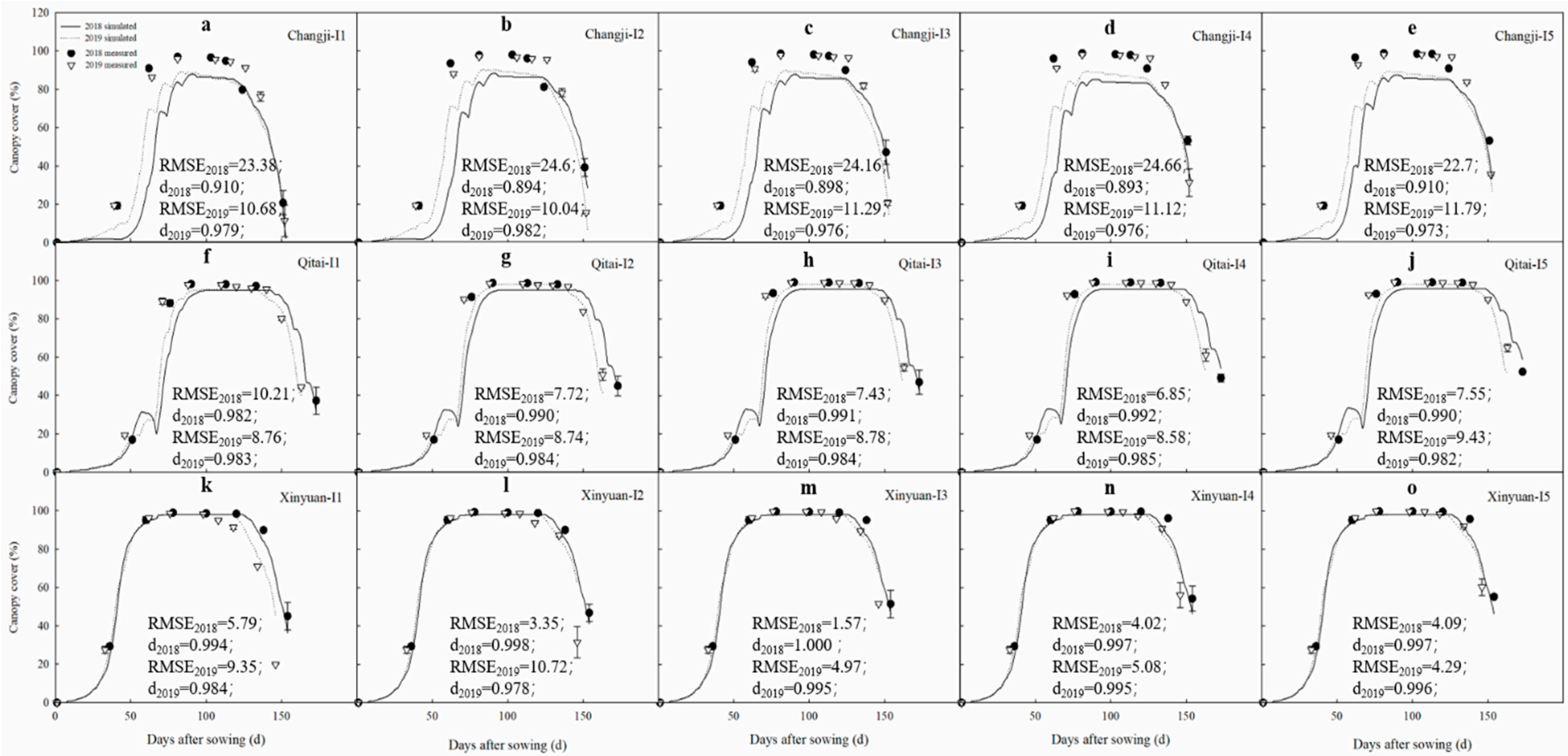

Figure 4. Simulated (line) and calculated canopy cover (points) in the growing seasons of maize. Note: (**a**) Changji I1, (**b**) Changji I2, (**c**) Changji I3, (**d**) Changji I4, (**e**) Changji I5, (**f**) Qitai I1, (**g**) Qitai I2, (**h**) Qitai I3, (**i**) Qitai I4, (**j**) Qitai I5, (**k**) Xinyuan I1, (**l**) Xinyuan I2, (**m**) Xinyuan I3, (**n**) Xinyuan I4, and (**o**) Xinyuan I5.

3.2. Transpiration, Biomass and Yield

The seasonal transpiration (Tr) showed a linear increase trend with an increase in irrigation amount (Table 5). The Tr was different for Changji, Qitai and Xinyuan. The Tr of Xinyuan was significantly higher than that of Changji and Qitai. The Tr was affected by the significant interaction of site × year and site × irrigation interaction.

Table 5. Biomass, Yield, Transpiration, WUE_B, WUE_Y and WP* from 2018 to 2019.

Site	Year	Irrigation (mm)	Biomass (Mg ha^{-1})	Yield (Mg ha^{-1})	Transpiration (mm)	WUE_B (kg m^{-3})	WUE_Y (kg m^{-3})	WP* (g m^2 d^{-1})
Changji	2018	I1 (450)	24.4 c	12.3 d	357.2 c	7.2 d	3.4 c	32.1 d
		I2 (540)	28.9 b	14.2 c	369.9 b	8.0 c	3.8 c	37.4 c
		I3 (630)	32.1 ab	15.3 b	373.0 a	8.8 b	4.1 b	41.2 b
		I4 (720)	35.0 a	16.3 a	374.4 a	9.2 a	4.4 a	45.4 a
		I5 (810)	36.6 a	16.6 a	377.8 a	9.3 a	4.4 a	45.8 a
	2019	I1 (450)	24.6 d	11.4 d	397.4 c	6.2 d	2.9 c	32.3 d
		I2 (540)	29.2 c	13.0 c	425.3 b	6.9 c	3.1 c	36.0 c
		I3 (630)	32.4 b	14.1 b	428.4 b	7.6 b	3.3 b	38.7 b
		I4 (720)	36.6 a	15.1 a	434.0 a	8.4 a	3.5 a	43.4 a
		I5 (810)	37.4 a	15.7 a	434.0 a	8.6 a	3.6 a	44.1 a
Qitai	2018	I1 (360)	31.0 c	16.0 c	336.7 c	9.2 c	4.8 c	34.6 c
		I2 (450)	33.6 b	17.1 b	345.2 b	9.7 bc	5.0 b	37.0 b
		I3 (540)	36.1 a	18.7 a	346.8 ab	10.4 ab	5.4 a	39.0 b
		I4 (630)	37.9 a	18.6 a	350.2 a	10.8 a	5.3 a	40.7 a
		I5 (720)	38.6 a	18.5 a	348.4 a	11.1 a	5.3 a	41.3 a
	2019	I1 (360)	32.5 c	15.8 c	350.2 c	9.3 c	4.5 c	34.3 c
		I2 (450)	35.6 b	17.7 b	365.5 b	9.7 b	4.8 b	36.4 b
		I3 (540)	37.8 a	18.9 a	368.2 ab	10.3 a	5.1 a	38.2 ab
		I4 (630)	38.6 a	18.9 a	370.4 a	10.4 a	5.1 a	39.1 a
		I5 (720)	39.2 a	18.3 a	369.4 a	10.6 a	5.0 ab	39.4 a
Xinyuan	2018	I1 (90)	35.5 c	16.1 b	525.5 c	6.8 bc	3.1 a	36.4 b
		I2 (180)	39.0 b	17.6 a	586.6 b	6.6 c	3.0 b	36.1 b
		I3 (270)	40.5 a	17.9 a	594.9 a	6.8 bc	3.0 b	37.9 a
		I4 (360)	41.5 a	17.0 a	593.6 a	7.0 ab	2.9 b	38.0 a
		I5 (450)	41.6 a	15.6 b	583.7 b	7.1 a	2.7 c	39.1 a
	2019	I1 (0)	30.7 d	14.1 d	428.1 d	7.1 a	3.3 a	41.4 a
		I2 (90)	34.4 c	16.3 c	515.2 c	6.7 c	3.2 b	37.9 c
		I3 (180)	37.9 b	18.4 ab	561.3 b	6.8 bc	3.3 ab	37.8 c
		I4 (270)	39.1 ab	18.6 a	576.4 a	6.8 bc	3.2 ab	39.3 bc
		I5 (360)	39.7 a	16.8 b	574.2 a	6.9 b	2.9 c	39.9 ab
	Source of variation							
	Site		**	**	**	**	**	**
	Year		ns	*	**	**	**	ns
	Irrigation		**	**	**	**	**	**
	Site × Year		**	**	**	**	**	**
	Site × Irrigation		**	**	**	**	**	**
	Year × Irrigation		ns	ns	ns	ns	ns	ns
	Site × Year × Irrigation		ns	ns	ns	ns	ns	ns

Note: Different letters mean significant differences at $p < 0.05$. * $p < 0.05$; ** $p < 0.01$; ns, no significance.

Increasing the irrigation amount significantly increased the biomass in Changji, Qitai and Xinyuan (Table 5). The biomass was affected by the significant interaction of site × year and site × irrigation interaction.

Maize yield showed a linear increase trend with the increase in irrigation amount at Changji and Qitai. However, yield increased first and then decreased with the increase in irrigation at Xinyuan (Table 5). The maize yield under drip irrigation varied with climatic conditions. Changji had the lowest yield (11.4–16.6 Mg ha^{-1}), followed by Xinyuan (14.1–18.6 Mg ha^{-1}), and Qitai had the highest yield (15.8–18.9 Mg ha^{-1}). The yield was affected by the significant interaction of site × year and site × irrigation interaction.

3.3. Water Use Efficiency and Normalized Water Productivity

Water use efficiency was divided into average water use efficiency of biomass (WUE_B) and yield (WUE_Y) (Table 5). In Changji and Qitai, I1 had the lowest WUE_B, and over-irrigation (I5) had the highest WUE_B, indicating that the amount of irrigation increased the WUE_B. However, the WUE_B (6.9–7.1 kg m^{-3}, 2019) of I1 in Xinyuan may be due to the fact that the lack of irrigation during the whole growth period significantly reduced transpiration. The changing trend of WUE_Y was consistent with WUE_B. The mean WUE_B varied fort all irrigation treatments at the three experiment sites. Xinyuan had the lowest WUE_B (6.8 kg m^{-3}), followed by Changji (7.6 kg m^{-3}), and Qitai had the highest WUE_B (10.4 kg m^{-3}). The WUE_B and WUE_Y were affected by the significant interaction of site × year and site × irrigation interactions. The average value of maize WUE_B was 7.23 kg m^{-3} (R^2 = 0.8720, Figure 5b).

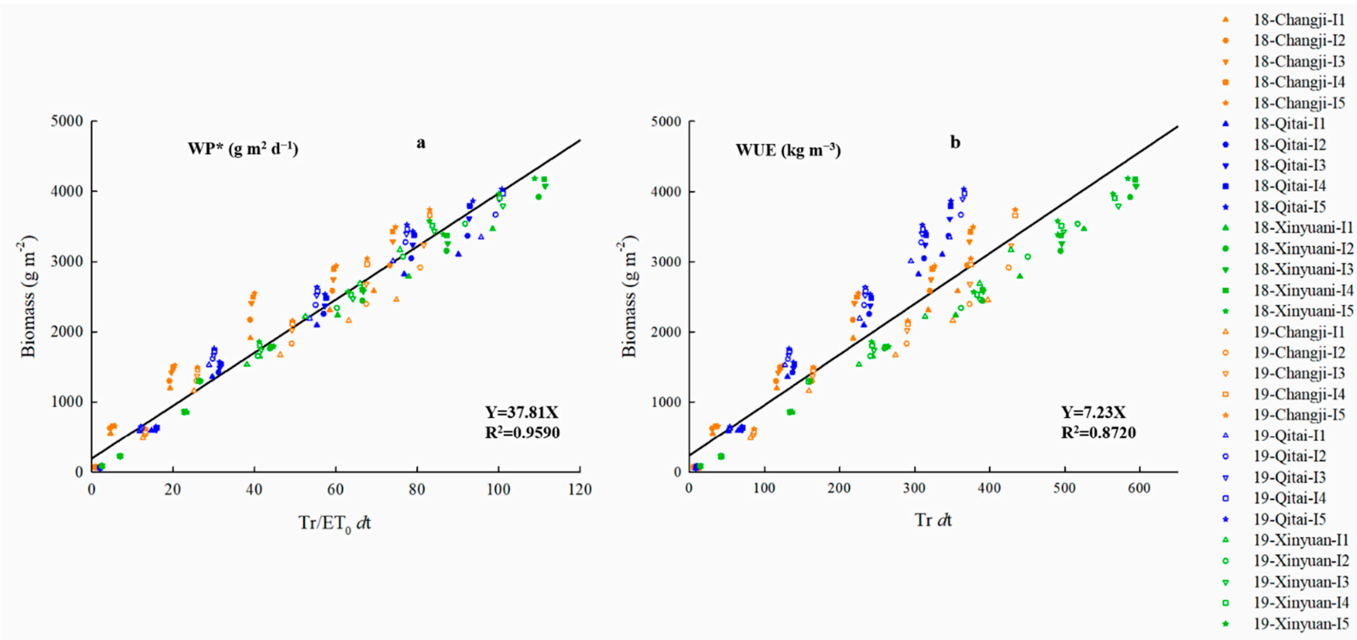

Figure 5. Relationships between above ground biomass and integral of actual transpiration (**a**) with integral of normalized transpiration (**b**) over time for maize in Changji, Qitai and Xinyuan in 2018 and 2019.

WP* was determined based on the measured biomass and normalized transpiration during the growth period of maize in Changji, Qitai and Xinyuan (Table 5). The increase in irrigation amount significantly increased WP*. However, I1 (2019) calculated the highest WP* at Xinyuan. The mean WP* of all irrigation treatments was 37.69, 38.76 and 39.01 g m^{-2} d^{-1} for Xinyuan, Qitai and Changji, respectively. The WP* was affected by the significant interaction of site × year and site × irrigation. Under the film mulch and dense planting mode, the average value of drip maize WP* was 37.81 g m^{-2} d^{-1} (R^2 = 0.9590, Figure 5a).

4. Discussion

4.1. AquaCrop Model Parameterization under Film-Mulched Drip Irrigation and Dense Planting

According to the setting of surface cover parameters in the management module of the AquaCrop model, some crop parameters of the model can be calibrated by actually observing the response of seed maize yield to the surface mulching [13]. This study proved that this calibration method was feasible for film-mulched drip irrigation maize in arid, semi-arid and semi-humid areas. Compared with the improvement of AquaCrop by determining the quantitative relationship between geothermal and air temperature [22,23], our method was simpler and more direct. At the same time, it was proven that the provided conservative parameter by Hsiao et al. (2009) was also applicable for drip maize under dense planting [9].

The core goal of AquaCrop was to calculate daily biomass using normalized water productivity (WP*) and daily ET_0 simulated daily Tr [8,34]. In this study, we determined that the increase in irrigation lead to an increase in drip maize WP* under film-mulched and dense planting in arid, semi-arid and semi-humid areas. There were significant interactive effects on WP* between site × year and site × irrigation. However, this effect may come from the soil properties and irrigation measures at the different sites. The soils were light loam in Changji, heavy loam in Qitai, and medium loam in Xinyuan. The first irrigation was V6 (jointing stage) in Changji, V9 in Qitai, and V12 in Xinyuan. According to the relationship between the measured biomass of maize and actual transpiration integral and normalized transpiration integral, the average WP* was 37.81 g m^{-2} d^{-1}, and the average WUE_B was 7.23 kg m^{-3}. The relationship between biomass and normalized transpiration (Figure 5a) showed a substantially greater coefficient of determination (R^2 = 0.9590) than the linear regression (R^2 = 0.8720) between biomass and actual transpiration (Figure 5b). This shows that WUE_B was greatly affected by the year, site and irrigation, but the response of WP* was relatively stable under different sites, years and irrigation. Therefore, WP* can be used as a good indicator to study the relationship between crops and water use and predict crop yields under the background of crop climate change.

At the beginning of the AquaCrop model design, the commonly used farmland surface cover and farming techniques were not considered enough. In this study, our estimate of WP* (37.81 g m^{-2} d^{-1}) and the value reported by 33.7 g m^{-2} d^{-1} [9] increased by 4.11 g m^{-2} d^{-1}. The WP* is also higher than that of FAO, the default value of C_4 plants in the AquaCrop model (30 g m^{-2} d^{-1} to 35 g m^{-2} d^{-1}). This result shows that the drip maize under film-mulched and dense planting conditions is different from others. Ran et al. (2018) calculated that the WP* was 20.9 g m^{-2} d^{-1} for seed maize production under film mulching and border irrigation in the Shiyang River area [13]. However, He et al. (2020) confirmed that the maize WP* was 23.2 g m^{-2} d^{-1} under film mulching and drip irrigation in this area [14]. This shows that although WP* does not change with annual climate, it may be affected by planting patterns, management measures and varieties. Therefore, it is necessary to conduct continuous experiments to verify the consistency of WP* in different ecological areas, planting modes, management measures and varieties. This will provide a scientific basis and technical support for the productivity prediction and optimal management of water resources for maize in arid, semi-arid and semi-humid areas.

4.2. Evaluation of Parametric AquaCrop Model Simulation

The driving factor of the AquaCrop model is water availability [9]. Therefore, accurately simulating the dynamic changes of soil water is the basis of the model. In this study, the observed and simulated values of soil water storage were generally consistent at a depth of 0–100 cm during the maize growth period in the arid, semi-arid and semi-humid areas. However, the simulation accuracy of the measured value was poor. The reasons for this may be the following: one is the evapotranspiration of water caused by the lag of the measurement time, the other is the spatial variation when rainfall occurs, and the third is the interception of plastic film and maize plant leaves. This shows that AquaCrop can reflect the change of soil water in the field, but it was not suitable for the prediction of soil water with film-mulched drip irrigation. In addition, the AquaCrop model only considers vertical input (rainfall, irrigation and capillary rise) and output (evaporation, transpiration and deep infiltration) for soil water balance and does not distinguish the difference in soil water transport under different irrigation conditions. For example, soil water was a two-dimensional movement form under furrow and border irrigation [40]. However, it was a three-dimensional movement form under drip irrigation [41]. Therefore, how to combine multi-dimensional water movement models, such as Hydrus [42], to obtain more accurate soil water data may be a new way to improve the simulation accuracy of the AquaCrop model.

It is generally believed that the AquaCrop model can simulate the growth of maize under full irrigation and mild stress conditions [9,10]. However, the model is sensitive to water stress during the vegetative growth period, which leads to underestimation of the occurrence stage of canopy coverage [43,44]. In this study, the parametric AquaCrop model can simulate the canopy coverage of film-mulched drip maize in arid, semi-arid and semi-humid areas. The simulation accuracy of high irrigation was higher than that of low irrigation. From arid to semi-humid areas, the simulation accuracy of the model gradually improved. The reason was that maize was not irrigated in seedlings in V6 (arid areas) and V9 (semi-arid areas). This led to an underestimated expansion of maximum canopy coverage. Therefore, the model needs to establish a refined parameter set to improve the simulation accuracy.

The AquaCrop model assumes that the field is uniform. It requires no spatial differences in crop development, transpiration, soil characteristics or management [9,34]. Currently, most simulations of maize yield are on a single field scale (point simulation) [45]. However, in the wide area, due to differences in soil texture and management measures, model parameter calibration and verification are poor. Therefore, in order to apply the AquaCrop model onto a wider area, it may be necessary to combine multi-year data or multi-site data to verify the model parameters. At the same time, it may also be necessary to combination remote sensing technology [46], climate models [47,48] and economic models [49] with the AquaCrop model.

5. Conclusions

The increase in irrigation led to an increase in maize yield, biomass, transpiration, water use efficiency, and normalized water productivity (WP*). Yield, biomass, transpiration and WUE varied substantially and significantly between sites, irrigation and years. WP* varied significantly between sites and irrigation or their interactions, showing an overall value of 37.81 g m^{-2} d^{-1}. The WP* differed fundamentally from the conventional parameter for water productivity, but it is a useful parameter for assessing the attainable rate of drip-irrigated maize under dense planting in arid to semi-humid climates. The parametric model could simulate the maize canopy coverage well, especially for high irrigation in semi-humid areas. However, the parametric AquaCrop model was not suitable for the prediction of soil water. One way to improve the accuracy of water simulation in a drip irrigation maize field may be to combine a multi-dimensional water movement model with AquaCrop in the future.

Author Contributions: Conceptualization, L.Z. and S.L.; methodology, F.W.; software, F.W. and L.Z.; validation, F.W., L.Z., and B.M.; formal analysis, R.X.; investigation, J.X.; resources, K.W. and P.H.; data curation, J.X. and F.W.; writing—original draft preparation, F.W.; writing—review and editing, F.W., R.X. and L.Z.; visualization, B.M.; supervision, J.X., L.Z., and S.L.; project administration, F.W. and S.L.; funding acquisition, S.L. All authors have read and agreed to the published version of the manuscript.

Funding: This work was supported by grants from the Agricultural Science and Technology Innovation Program (CAAS-ZDRW202004), Basic Scientific Research Fund of Chinese Academy of Agricultural Sciences (S2021ZD05), China Agriculture Research System of MOF and MARA(CARS-02).

Data Availability Statement: The data that support the findings of this study are available from the corresponding authors upon reasonable request.

Acknowledgments: We are also grateful to the staff from the Changji, Qitai and Xinyuan Experiment Site, who provided the technical support for this study.

Conflicts of Interest: The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Acronyms: LA (cm^2), leaf area per plant; LAI, leaf area index; CC (%), canopy coverage; SWC (%), soil water content; SWS (mm), soil water storage; ET_0 (mm d^{-1}), daily reference evapotranspiration; Tr (mm d^{-1}), daily transpiration by a crop; B (g m^2), aboveground biomass; WUE (kg m^{-3}), water-use efficiency; WUE_B (kg m^{-3}), water-use efficiency of biomass for a crop that is final dry mater divided by total transpiration during a crop growing season; WUE_Y (kg m^{-3}), water-use efficiency of yield for a crop that is yield divided by total transpiration during a crop growing season; WP* (g m^{-2} d^{-1}), normalized water productivity calculated as crop biomass divided by the integral of daily Tr/ET_0 from sowing to harvest.

References

1. Hamdy, A.; Ragab, R.; Scarascia-Mugnozza, E. Coping with water scarcity: Water saving and increasing water productivity. *Irrig. Drain.* **2003**, *52*, 3–20. [CrossRef]
2. Sowers, J.; Vengosh, A.; Weinthal, E. Climate change, water resources, and the politics of adaptation in the Middle East and North Africa. *Clim. Chang.* **2010**, *104*, 599–627. [CrossRef]
3. Bozkurt, S.; Yazar, A.; Mansurolu, G.S. Effects of different drip irrigation amounts on yield and some agronomic characteristics of raised bed planted corn. *Afr. J. Agric. Res.* **2011**, *6*, 5291–5300. [CrossRef]
4. Hao, B.Z.; Xue, Q.W.; Marek, T.H.; Jessup, K.E.; Hou, X.B.; Xu, W.W.; Bynum, E.D.; Bean, B.W. Soil water extraction, water use, and grain yield by drought-tolerant maize on the Texas High Plains. *Agric. Water Manag.* **2015**, *155*, 11–21. [CrossRef]
5. Kang, S.Z.; Hao, X.M.; Du, T.S.; Tong, L.; Su, X.L.; Lu, H.N.; Li, X.L.; Huo, Z.L.; Li, S.E.; Ding, R.S. Improving agricultural water productivity to ensure food security in China under changing environment: From research to practice. *Agric. Water Manag.* **2017**, *179*, 5–17. [CrossRef]
6. Geerts, S.; Raes, D. Deficit irrigation as an on-farm strategy to maximize crop water productivity in dry areas. *Agric. Water Manag.* **2009**, *96*, 1275–1284. [CrossRef]
7. FAO. *How to Feed the World in 2050. Issue Brief from the High-Level Expert Forum Held in Rome, 12–13 October*; FAO: Rome, Italy, 2009.
8. Raes, D.; Steduto, P.; Hsiao, T.C.; Fereres, E. AquaCrop—The FAO Crop Model to Simulate Yield Response to Water: II. Main Algorithms and Software Description. *Agron. J.* **2009**, *101*, 438–447. [CrossRef]
9. Hsiao, T.C.; Heng, L.; Steduto, P.; Rojas-Lara, B.; Raes, D.; Fereres, E. AquaCrop—The FAO Crop Model to Simulate Yield Response to Water: III. Parameterization and Testing for Maize. *Agron. J.* **2009**, *101*, 448–459. [CrossRef]
10. Heng, L.K.; Hsiao, T.; Evett, S.; Howell, T.; Steduto, P. Validating the FAO AquaCrop Model for Irrigated and Water Deficient Field Maize. *Agron. J.* **2009**, *101*, 488–498. [CrossRef]
11. Abedinpour, M.; Sarangi, A.; Rajput, T.B.S.; Singh, M.; Pathak, H.; Ahmad, T. Performance evaluation of AquaCrop model for maize crop in a semi-arid environment. *Agric. Water Manag.* **2012**, *110*, 55–66. [CrossRef]
12. Paredes, P.; de Melo-Abreu, J.; Alves, I.; Pereira, L. Assessing the performance of the FAO AquaCrop model to estimate maize yields and water use under full and deficit irrigation with focus on model parameterization. *Agric. Water Manag.* **2014**, *144*, 81–97. [CrossRef]
13. Ran, H.; Kang, S.Z.; Li, F.S.; Du, T.S.; Tong, L.; Li, S.; Ding, R.S.; Zhang, X.T. Parameterization of the AquaCrop model for full and deficit irrigated maize for seed production in arid Northwest China. *Agric. Water Manag.* **2018**, *203*, 438–450. [CrossRef]
14. He, Q.S.; Li, S.; Hu, D.; Wang, Y.H.; Cong, X. Performance assessment of the AquaCrop model for film-mulched maize with full drip irrigation in Northwest China. *Irrig. Sci.* **2021**, *39*, 277–292. [CrossRef]
15. Andarzian, B.; Bannayan, M.; Steduto, P.; Mazraeh, H.; Barati, M.; Rahnama, A. Validation and testing of the AquaCrop model under full and deficit irrigated wheat production in Iran. *Agric. Water Manag.* **2011**, *100*, 1–8. [CrossRef]
16. Toumi, J.; Er-Raki, S.; Ezzahar, J.; Khabba, S.; Jarlan, L.; Chehbouni, A. Performance assessment of AquaCrop model for estimating evapotranspiration, soil water content and grain yield of winter wheat in Tensift Al Haouz (Morocco): Application to irrigation management. *Agric. Water Manag.* **2016**, *163*, 219–235. [CrossRef]
17. Jalil, A.; Akhtar, F.; Awan, U.K. Evaluation of the AquaCrop model for winter wheat under different irrigation optimization strategies at the downstream Kabul River Basin of Afghanistan. *Agric. Water Manag.* **2020**, *240*, 106321. [CrossRef]
18. Maniruzzaman, M.; Talukder, M.S.U.; Khan, M.H.; Biswas, J.C.; Nemes, A. Validation of the AquaCrop model for irrigated rice production under varied water regimes in Bangladesh. *Agric. Water Manag.* **2015**, *159*, 331–340. [CrossRef]
19. Farahani, H.J.; Izzi, G.; Oweis, T.Y. Parameterization and Evaluation of the AquaCrop Model for Full and Deficit Irrigated Cotton. *Agron. J.* **2009**, *101*, 469–476. [CrossRef]
20. Linker, R.; Ioslovich, I.; Sylaios, G.; Plauborg, F.; Battilani, A. Optimal model-based deficit irrigation scheduling using AquaCrop: A simulation study with cotton, potato and tomato. *Agric. Water Manag.* **2016**, *163*, 236–243. [CrossRef]
21. Tsakmakis, I.D.; Kokkos, N.P.; Gikas, G.D.; Pisinaras, V.; Hatzigiannakis, E.; Arampatzis, G.; Sylaios, G.K. Evaluation of AquaCrop model simulations of cotton growth under deficit irrigation with an emphasis on root growth and water extraction patterns. *Agric. Water Manag.* **2019**, *213*, 419–432. [CrossRef]
22. Liu, Q.; Gong, D.Z.; Hao, W.P.; Wang, H.B.; Gao, X.; Mei, X.R. Yield of film mulched maize with AquaCrop Mode. *J. Irrig. Drain.* **2015**, *34*, 54–61, (In Chinese with English abstract). [CrossRef]
23. Yang, N.; Sun, Z.X.; Zhang, L.Z.; Zheng, J.M.; Feng, L.S.; Li, K.Y.; Zhang, Z.; Feng, C. Simulation of water use process by film mulched cultivated maize based on improved AquaCrop model and its verification. *Trans. CSAE* **2015**, *31*, 122–132, (In Chinese with English abstract). [CrossRef]
24. Fu, C.; Li, S.S.; Li, J.; Wang, Y.C.; Lu, Y.S.; Xu, W.Z.; Wei, S. Calibration and Validation of AquaCrop Model in Spring Wheat Region of Songnen Plain. *J. Irrig. Drain.* **2012**, *31*, 99–102, (In Chinese with English abstract). [CrossRef]

25. Wang, X.X.; Wang, Q.J.; Fan, J.; Fu, Q.P. 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 Manag.* **2013**, *129*, 95–104. [CrossRef]
26. Shao, D.G.; Le, Z.H.; Xu, B.L.; Hu, N.J.; Tian, Y.N. Optimization of irrigation scheduling for organic rice based on AquaCrop. *Trans. Chin. Soc. Agric. Eng.* **2018**, *34*, 114–122. [CrossRef]
27. Chen, R.; Cheng, W.H.; Cui, J.; Liao, J.; Fan, H.; Zheng, Z.; Ma, F.Y. Lateral spacing in drip-irrigated wheat: The effects on soil moisture, yield, and water use efficiency. *Field Crops Res.* **2015**, *179*, 52–62. [CrossRef]
28. Wu, Y.; Huang, F.Y.; Jia, Z.K.; Ren, X.L.; Cai, T. Response of soil water, temperature, and maize (*Zea may* L.) production to different plastic film mulching patterns in semi-arid areas of northwest China. *Soil Tillage Res.* **2017**, *166*, 113–121. [CrossRef]
29. Zhao, Y.G.; Li, Y.Y.; Wang, J.; Pang, H.C.; Li, Y. Buried straw layer plus plastic mulching reduces soil salinity and increases sunflower yield in saline soils. *Soil Tillage Res.* **2016**, *155*, 363–370. [CrossRef]
30. Fan, Y.Q.; Ding, R.S.; Kang, S.Z.; Hao, X.M.; Du, T.S.; Tong, L.; Li, S. Plastic mulch decreases available energy and evapotranspiration and improves yield and water use efficiency in an irrigated maize cropland. *Agric. Water Manag.* **2017**, *179*, 122–131. [CrossRef]
31. Wang, F.X.; Wu, X.X.; Shock, C.C.; Chu, L.Y.; Gu, X.X.; Xue, X. Effects of drip irrigation regimes on potato tuber yield and quality under plastic mulch in arid Northwestern China. *Field Crops Res.* **2011**, *122*, 78–84. [CrossRef]
32. He, H.B.; Ma, F.Y.; Yang, R.; Chen, L.; Jia, B.; Cui, J.; Fan, H.; Wang, X.; Li, L. Rice Performance and Water Use Efficiency under Plastic Mulching with Drip Irrigation. *PLoS ONE* **2013**, *8*, e83103. [CrossRef] [PubMed]
33. Li, Z.; Zhang, R.; Wang, X.; Chen, F.; Lai, D.; Tian, C. Effects of plastic film mulching with drip irrigation on N2O and CH4 emissions from cotton fields in arid land. *J. Agric. Sci.* **2014**, *152*, 534–542. [CrossRef]
34. Steduto, P.; Hsiao, T.C.; Fereres, E. On the conservative behavior of biomass water productivity. *Irrig. Sci.* **2007**, *25*, 189–207. [CrossRef]
35. Wang, F.; Xiao, J.F.; Ming, B.; Xie, R.Z.; Wang, K.R.; Hou, P.; Liu, G.Z.; Zhang, G.Q.; Chen, J.L.; Liu, W.M.; et al. Grain yields and evapotranspiration dynamics of drip-irrigated maize under high plant density across arid to semi-humid climates. *Agric. Water Manag.* **2021**, *247*, 106726. [CrossRef]
36. Allen, R.G.; Pereira, L.S.; Raes, D.; Smith, M. *Crop Evapotranspiration-Guidelines for Computing Crop Water Requirements, Irrigation and Drain*; Paper No. 56; FAO: Rome, Italy, 1998; p. 300.
37. Yuan, M.; Zhang, L.; Gou, F.; Su, Z.; Spiertz, J.H.J.; van der Werf, W. Assessment of crop growth and water productivity for five C3 species in semi-arid Inner Mongolia. *Agric. Water Manag.* **2013**, *122*, 28–38. [CrossRef]
38. Steduto, P.; Hsiao, T.C.; Raes, D.; Fereres, E. AquaCrop—The FAO Crop Model to Simulate Yield Response to Water: I. Concepts and Underlying Principles. *Agron. J.* **2009**, *101*, 426–437. [CrossRef]
39. Willmott, C.J. Some comments on the evaluation of model performance. *Bull. Am. Meteorol. Soc.* **1982**, *63*, 1309–1313. [CrossRef]
40. Tabuada, M.A.; Rego, Z.J.C.; Vachaud, G.; Pereira, L.S. Modelling of furrow irrigation. Advance with two-dimensional infiltration. *Agric. Water Manag.* **1995**, *28*, 201–221. [CrossRef]
41. Fernández-Gálvez, J.; Simmonds, L.P. Monitoring and modelling the three-dimensional flow of water under drip irrigation. *Agric. Water Manag.* **2006**, *83*, 197–208. [CrossRef]
42. Azad, N.; Behmanesh, J.; Rezaverdinejad, V.; Abbasi, F.; Navabian, M. Developing an optimization model in drip fertigation management to consider environmental issues and supply plant requirements. *Agric. Water Manag.* **2018**, *208*, 344–356. [CrossRef]
43. Katerji, N.; Campi, P.; Mastrorilli, M. Productivity, evapotranspiration, and water use efficiency of corn and tomato crops simulated by AquaCrop under contrasting water stress conditions in the Mediterranean region. *Agric. Water Manag.* **2013**, *130*, 14–26. [CrossRef]
44. Ahmadi, S.H.; Mosallaeepour, E.; Kamgar-Haghighi, A.A.; Sepaskhah, A.R. Modeling Maize Yield and Soil Water Content with AquaCrop Under Full and Deficit Irrigation Managements. *Water Resour. Manag.* **2015**, *29*, 2837–2853. [CrossRef]
45. Li, J.; Zhu, T.; Mao, X.M.; Adeloye, A.J. Modeling crop water consumption and water productivity in the middle reaches of Heihe River Basin. *Comput. Electron. Agric.* **2016**, *123*, 242–255. [CrossRef]
46. Han, C.Y.; Zhang, B.Z.; Chen, H.; Liu, Y.; Wei, Z. Novel approach of upscaling the FAO AquaCrop model into regional scale by using distributed crop parameters derived from remote sensing data. *Agric. Water Manag.* **2020**, *240*, 106288. [CrossRef]
47. Abedinpour, M.; Sarangi, A.; Rajput, T.B.S.; Singh, M. Prediction of maize yield under future water availability scenarios using the AquaCrop model. *J. Agric. Sci.* **2014**, *152*, 558–574. [CrossRef]
48. Yang, C.Y.; Fraga, H.; Van Ieperen, W.; Santos, J.A. Assessment of irrigated maize yield response to climate change scenarios in Portugal. *Agric. Water Manag.* **2017**, *184*, 178–190. [CrossRef]
49. García-Vila, M.; Fereres, E. Combining the simulation crop model AquaCrop with an economic model for the optimization of irrigation management at farm level. *Eur. J. Agron.* **2012**, *36*, 21–31. [CrossRef]