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Performance of AquaCrop Model for Maize Growth Simulation under Different Soil Conditioners in Shandong Coastal Area, China

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Abstract: Evaluating the performance of AquaCrop models under the drip irrigation of maize with soil conditioners is of great significance for improving coastal saline–alkali land crop management strategies. This study aimed to evaluate the performance of an AquaCrop model for maize growth simulation under different soil conditions (humic acid (HA) and sodium carboxymethyl cellulose (CMC)) and dosages and different levels of irrigation in the Shandong coastal saline–alkali area, China, and to optimize the amount of irrigation. Three years of experiments were carried out in the growing season of maize (Ludan 510) in 2019, 2020, and 2021. The dosages of HA were 5, 15, 25, and 35 g/m^2, the dosages of CMC were 1, 2, 3, and 5 g/m^2, and the levels of irrigation from 2019 to 2021 were all 120 mm. The model was calibrated with data from 2019, and the model was verified with data from 2020 to 2021, according to the recommended corn parameters in the AquaCrop model manual. The results showed that the model had a good simulation effect on canopy coverage, with a root-mean-square error (RMSE) of less than 15.2%, and the simulated aboveground biomass and yield were generally low. The simulated value of soil water content was generally high, with some treatments having errors of more than 15.0%. The simulation effect of irrigated maize from 2019 to 2020 was better than maize in 2021. The simulation effect of HA was better than that of CMC, while the simulation effect of a low-gradient modifier was better than that of high-gradient conditioner when compared with CMC. In conclusion, the AquaCrop model could be a viable method for predicting maize development under different soil conditioners in this area. The suitable levels of irrigation under HA and CMC treatments were 47.0–65.9 mm and 61.0–92.4 mm, respectively, according to the principle of high yield and water use efficiency. The results provided a reference for optimizing the drip irrigation of maize under the application of soil conditioners in coastal saline–alkali areas.

Keywords: AquaCrop model; maize; humic acid; sodium carboxymethyl cellulose; levels of irrigation

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1. Introduction

About 20% of the world's agricultural land is irrigated, producing 45% of the food supply. Salt-affected soils account for more than 20% of the global irrigated area. In some countries, salt-affected soils are spread over more than half of the irrigated land [1]. It is becoming increasingly difficult for humans to maintain their fundamental survival needs as the demand for farmed land resources grows [2,3]. Maize is one of the three major food crops in China, and it is also the main food crop in the Yellow River Delta [4]. The study of the reasonable degrees of irrigation for maize is critical for improving crop productivity, water conservation, water usage efficiency, soil water, and the salt environment.

Dongying City, Shandong Province, is located in the Yellow River Delta of China. Due to the particularity of the geographical location and the concentrated distribution of rainfall from July to August each year, soil salinization is particularly serious, forming a typical coastal saline–alkali land [5]. The natural geology of coastal saline–alkali land is complicated, with high groundwater salinity and shallow groundwater levels. Conventional improvement measures, such as traditional engineering, chemical improvement, and biological improvement, may have an adverse effect on the long-term use of coastal saline–alkali land [6–10]. Water and salt stress can inhibit maize root growth and reduce yield [11]. HA has been demonstrated in studies to improve soil structure, reduce salinity, and increase soil organic matter content, all of which can help crops develop and yield more successfully [12–19]. CMC is a water-soluble polymer that can improve soil shear strength and anti-erosion, improve soil structure and water-holding capacity, limit soil water infiltration, inhibit soil evaporation, and boost crop growth [20–26].

Crop growth models are computer-assisted dynamic simulations of crop growth and yield production, as well as crop reactions to environmental changes in the crop–soil–atmosphere systems [27]. Many crop models, such as CROPWAT [28], DSSAT [29], WOFOST [30], STICS [31], MOMOS [32], and Crop-Syst [33], have been established after extensive research based on various crop and driving principles. Simulations of crop development and growth parameters are based on complex interactions between climate variables, crops, soil parameters, and management practices. Most models necessitate extremely specific crop growth input data and statistics, and some models cannot be used in certain locations. Among these models, the AquaCrop model is a water-driven tool created and introduced by the Food and Agriculture Organization of the United Nations to simulate crop water productivity. It can be widely used in space and time by standardizing the water productivity parameters of the climate (including evaporation and atmospheric CO_2 concentration) [34]. In comparison with existing simulation models (such as DSSAT and WOFOST), the AquaCrop model features fewer input parameters, a broader application range, a simpler interface, good intuition, and high precision [35]. The model simulates crop yield using crop canopy coverage and harvest index under various management measures and irrigation modes [36], and then calculates crop water use efficiency to assess crop yield responses to water and determine the crop water response mechanism under various irrigation conditions [37]. Abedinpour et al. (2012) simulated maize in a semi-arid environment in India using the AquaCrop model, and found that it performed best for full irrigation and 25% deficit irrigation with normal N fertilizer [38]. Due to the short extension time of the AquaCrop model, there are relatively few studies on the applicability evaluation of the model in coastal saline–alkali land areas, especially studies of drip irrigation maize under the modifier conditions; elucidating the reasonable degree of irrigation is of great importance to saline–alkali land improvement and water-saving irrigation.

The purpose of this study was to analyze the effects of different irrigation quotas, different soil conditions, and application rates on canopy coverage, aboveground biomass, soil water content, and yield using 3-year field experiment data. The performance of the AquaCrop model in the simulation of maize growth in coastal saline–alkali land in Shandong Province, China, was evaluated to determine the applicability of the aquatic crop model in coastal saline–alkali land and provide reasonable levels of irrigation.

2. Materials and Methods

2.1. Experimental Site Description

The experimental site was between the high-tech demonstration base of Nonggao District, Guangrao County, Dongying City (37°21′ N, 118°57′ E, altitude 10 m), which is located in the Yellow River Delta in the north of Shandong Province, China, with a monsoon climate. The average sunshine duration is 2234 h per year, and the average precipitation over the year is 587.4 mm. The rainfall is mostly concentrated from June to September every year. The average temperature over the years is 12.3 °C, the annual average frost-free period is 198 days, and the buried depth of groundwater level was about 1 m in 2019–2021.

The physical properties of the soil are shown in Table 1. The soil in the experimental field was mainly sandy loam, with a soil bulk density of 1.45, saturated water content of 0.48, and field water-holding capacity of 0.15.

Table 1. Physical properties of soil.

Soil Depth cm	Clay %	Silt %	Sand %	Soil Texture	BD g/cm^3	SAT cm^3/cm^3	FC cm^3/cm^3
0–10	3.39	24.48	72.13	Sandy loam soil	1.40	0.46	0.16
10–20	2.18	18.37	79.45	Sandy loam soil	1.44	0.44	0.16
20–40	2.94	21.80	75.26	Sandy loam soil	1.43	0.45	0.15
40–60	6.73	55.41	37.86	Silt loam soil	1.48	0.53	0.15
60–80	7.64	50.92	41.44	Silt loam soil	1.46	0.53	0.14

BD is the soil bulk density, SAT is the soil volumetric saturated water content, and FC is the field capacity.

2.2. Experimental Design

The maize field experiment was conducted in the experimental station from 2019 to 2021, and it was developed using a single-factor, fully random experiment. The tested maize variety was "Jinan 30", the experimental plot area was approximately $2.5 \times 4 = 10$ m^2, and the total experiment design area was 270 m^2. Maize was planted in wide and narrow rows, with an 80 cm wide row spacing and a 40 cm narrow row spacing. The drip irrigation belt was laid in one pipe and two rows, with a dripper spacing of 30 cm, a dripper flow of 2 L/h, and a planting density of 25×60 cm. The field management mode was consistent with the local farmland management mode, such as fertilization and pesticides. The HA used in the experiment was produced by Xi'an Tianben Agricultural Chemistry Co., Ltd., Xi'an, China, and CMC was produced by Shandong Chemical Industry, China. The growth period of the maize in the test was about 125 d. The detailed pilot programs from 2019 to 2021 are detailed in Table 2. Four levels of humic acid (HA) dosages were set: 5 g/m^2 (H1), 15 g/m^2 (H2), 25 g/m^2 (H3), and 35 g/m^2 (H4). Four levels of sodium carboxymethyl cellulose (CMC) dosages were set: 1 g/m^2 (C1), 2 g/m^2 (C2), 3 g/m^2 (C3), and 5 g/m^2 (C4). The levels of irrigation of the maize in 2019, 2020, and 2021 were all 120 mm, which was full irrigation, in accordance with local experience [7].

Table 2. Crop parameters of the AquaCrop model.

Symbol	Description	Value	Unit	Remarks
	Basic parameters of maize crops			
CC_0	Initial canopy cover	1.50	%	Measured
CGC	Canopy growth coefficient	15.4	% day^{-1}	Calibrated
CCx	Maximum canopy cover	90	%	Measured
CDC	Canopy decline coefficient	11.0	% day^{-1}	Calibrated
Growth cycle	Time from sowing to emergence	7	–	Measured
	Time from sowing to maximum canopy coverage	50	–	Measured
	Time from sowing to senescence	82	days	Measured
	Time from sowing to maturity	105	days	Measured
	Time from sowing to flowering	80	days	Measured
	Flowering cycle	14	days	Measured
Z_m	Maximum effective rooting depth	1.0	m	Measured
–	Time from sowing to maximum root depth	78	–	Measured
HI_0	Reference harvest index	36	%	Calibrated
WP^*	Water productivity normalized for ETo and CO_2	18	g m^{-2}	Calibrated

Table 2. *Cont.*

Symbol	Description	Value	Unit	Remarks
	Parameters of water-stress response			
$P_{exp,upper}$	Fraction of TAW at which canopy expansion is limited	0.25	–	Calibrated
$P_{exp,lower}$	Fraction of TAW at which canopy expansion stops	0.55	–	Calibrated
$P_{clo,upper}$	Effect of water stress on stomatal conductance	0.20	–	Calibrated
$P_{clo,lower}$	Water stress had the least effect on stomatal conductance	0.50	–	Calibrated
$P_{sen,upper}$	Effect of water stress on early canopy senescence	0.55	–	Calibrated
	Parameters of salinity-stress response			
EC_{en}	ECe at which crop starts to be affected	1	dS m^{-1}	Calibrated
EC_{em}	ECe at which crop can no longer grow	15	dS m^{-1}	Calibrated
T_{base}	Substrate temperature	10	°C	Calibrated
T_{upper}	Upper limit temperature	30	°C	Calibrated

In the "Remarks" column, "Calibrated" indicates that the values were calibrated using the 2019 measured data, whereas "Measured" indicates measured data.

2.3. Observation Items and Methods

2.3.1. Meteorological Data

Meteorological data from maize sowing to maturity in 2019–2021 mainly included solar radiation, maximum temperature, minimum temperature, wind speed, relative humidity, and rainfall. The rainfall and reference crop evapotranspiration (ETo) during the maize growth period in 2019–2021 are shown in Figure 1, and the average rainfall values for each year were 440 mm, 528 mm, and 383 mm, respectively. After sowing, 0, 10, 20, 40, 60, 80, 100, and 120 became 00, 10, 15, 34, 53, 63, 79, and 89 growth stages of maize (BBCH scale), respectively.

2.3.2. Soil Water and Salt Content

The soil samples were taken after the sowing stage, seedling stage, heading stage, flowering stage, and graining stage, as well as harvest. The sampling depths of the soil samples were 5, 10, 15, 20, 30, 40, 50, 60, 70, and 80 cm, respectively, which were repeated three times. The drying method (105 ± 2 °C) was used to determine the soil water content. The soil salt content was measured with a DDS-307A conductivity meter (Shanghai Instrument & Electrical Scientific Instrument Co., Ltd., China). The conductivity of the soil saturated extract (EC_e) was estimated through the conductivity of the soil–water ratio of 1:5 ($EC_{1:5}$) [39].

$$EC_e = (2.46 + 3.03/\theta_{sp})EC_{1:5} \qquad (n = 344, r^2 = 0.993) \tag{1}$$

where θ_{sp} is the gravimetric water content of saturated paste (g/g). At our experimental site, the values of θ_{sp} were 0.42 and 0.40 for sandy loam soil and silt loam soil, respectively.

2.3.3. Canopy Cover

Six representative plants with uniform growth were selected in the experimental plot (three plants in the inner row and three plants in the outer row). The leaf areas of maize were measured manually in stages at 51 days, 70 days, 80 days, 93 days, and 105 days from sowing. The calculation formula of the green leaf area index is as follows [40]:

$$LAI = 0.75\rho\frac{\sum_{j=1}^{m}\sum_{i=1}^{n} L_{ij}B_{ij}}{m} \tag{2}$$

where LAI is the leaf area index, ρ is the plant density, m is the number of plants, n is the number of leaves per plant, L_{ij} is the maximum blade length, and B_{ij} is the maximum blade width.

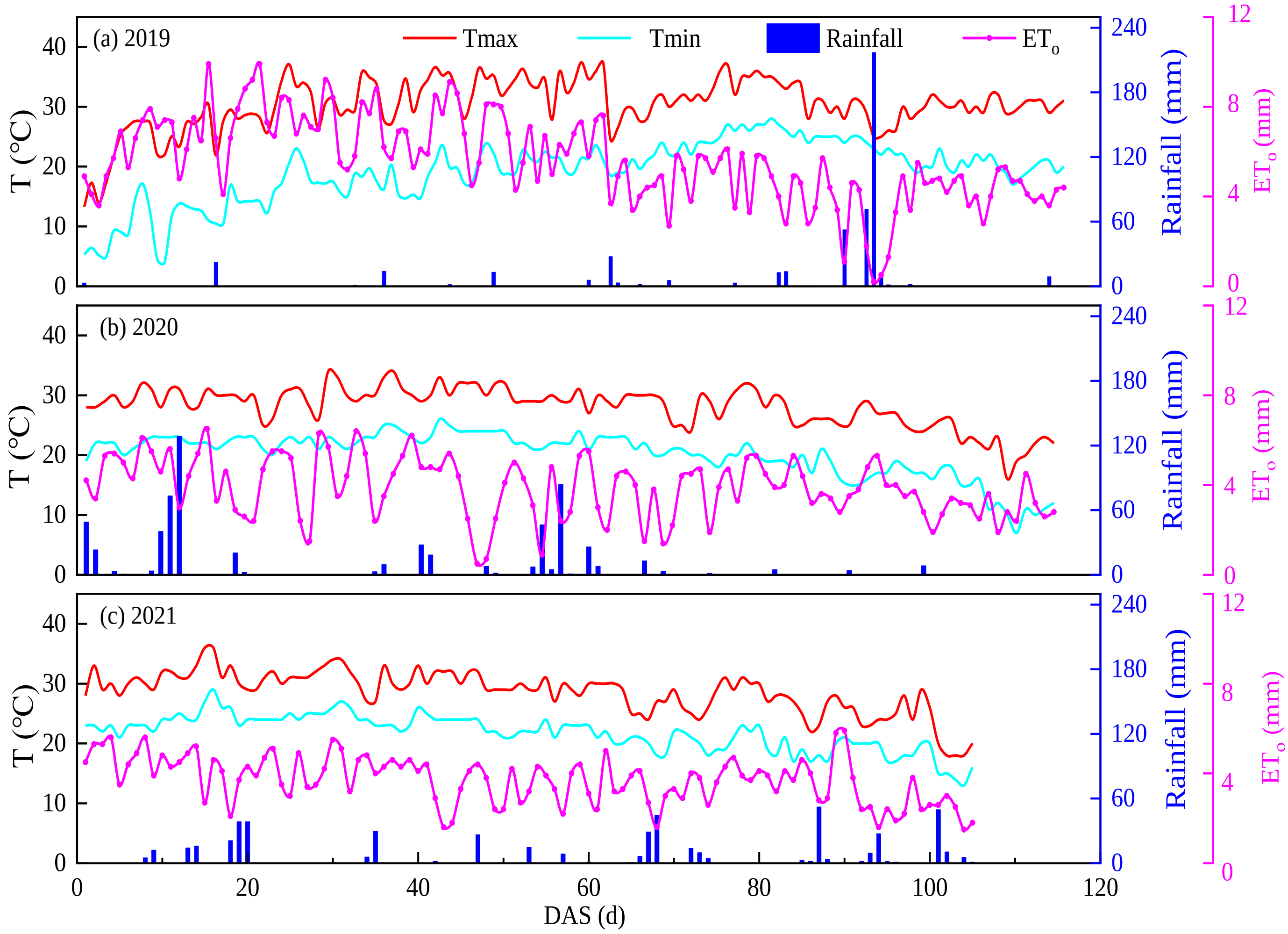

Figure 1. Meteorological data during the growth period of maize in 2019–2021. Tmax and Tmin are the maximum and minimum air temperature, respectively.

The canopy coverage (CC) can be calculated using the LAI [41].

$$CC = 1.005\left(1 - e^{-0.6LAI}\right)^{1.2} \tag{3}$$

2.3.4. Aboveground Biomass and Yield

At different growth stages, the stems and leaves of maize in the selected area were killed at 105 °C for 30 min, and dried at 75 °C for 48 h to constant weight, and then the dry weight of the maize stem and leaf was weighed to calculate the dry matter accumulation. After the maize had matured, 10 typical plants were selected from each plot to measure the ear weight and calculate the final yield. The AquaCrop model decomposes evapotranspiration (ET_c) into transpiration (T_r) and evaporation (E), and establishes a functional relationship between CC and reference crop evapotranspiration (ETo). The aboveground biomass (B) was estimated using calculated T_r and standard crop water productivity (WP*); then, B was converted to the final yield (Y) [41].

$$T_r = CC^* K_{cTr,x} ET_0 \tag{4}$$

$$E = K_r(1 - CC^*) K_{ex} ET_0 \tag{5}$$

$$B = WP \times (\frac{T_r}{ET_0}) \quad (6)$$

$$Y = f_{HI} HI_0 B \quad (7)$$

where CC^* is the canopy coverage adjusted by micro advection effect (%), $K_{cTr,x}$ is the maximum standard crop transpiration coefficient, K_r is the evaporation reduction coefficient used to adjust the impact of insufficient surface water, K_{ex} is the maximum soil evaporation coefficient, f_{HI} is a regulator of water stress, and HI_0 is the reference harvest index.

2.3.5. Water Use Efficiency

Water use efficiency (WUE) refers to the biomass or yield produced by consuming unit water, and its calculation formula is as follows [42,43]:

$$WUE = \frac{100Y}{ET} \quad (8)$$

where Y is the final yield (t/ha) and ET is the evapotranspiration of the whole growing season (mm).

2.4. AquaCrop Model Parameters

2.4.1. Crop Parameters

Crop parameters mainly include the crop growth period, initial crop canopy coverage (CC_0), maximum crop canopy coverage (CCx), crop water, and salt stress. This experiment adopted the field test data-driven model of the high-tech demonstration base in Nonggao District, Guangrao County, Dongying City, Shandong Province, China, from 2019 to 2021. Taking the aboveground biomass (B) and yield (Y) of maize as the objective functions, the simulation results of the model were matched with the measured results. Referring to the FAO AquaCrop model manual, according to the existing parameters and parameter range of corn as the initial value, the simulation value and the measured value were compared. The differences in canopy coverage, aboveground biomass, and yield between the simulated and measured values were analyzed, and the parameters were continuously adjusted until the simulated values were in good agreement with the measured values. The main crop parameters of the AquaCrop model are shown in Table 2.

2.4.2. Soil Parameters

The soil parameters mainly include the soil bulk density, saturated water content of each soil layer, field capacity, wilting water content, soil texture, and soil type. The measured soil parameters after applying the conditioners are shown in Table 3.

Table 3. Main physical properties of the soil after applying the conditioners.

Treatments	Depth (cm)	SAT_a (cm^3/cm^3)	FC_a cm^3/cm^3	PWP cm^3/cm^3	Ks (mm/d)
CK	0–80	44.00	23.36	5.18	230.40
H1	0–80	44.00	23.55	5.21	216.00
H2	0–80	44.37	23.64	5.40	207.36
H3	0–80	44.95	23.94	5.45	175.68
H4	0–80	45.60	24.37	5.69	175.68
C1	0–80	44.64	22.95	5.13	201.60
C2	0–80	44.65	22.23	5.19	175.68
C3	0–80	44.94	27.08	8.22	63.36
C4	0–80	45.26	26.17	8.04	48.00

SAT_a, FC_a, PWP, and Ks are the volumetric saturated water content, field capacity, wilting water content, and saturated hydraulic conductivity of soil after applying the conditioners, respectively.

2.4.3. Management Parameters

Management data include irrigation measures and field management. Irrigation measures include the irrigation mode, irrigation quota, irrigation cycle, and irrigation times. The experimental data of the irrigation quota design in the whole growth period of the maize were sorted and set as non-coverage and non-ridge in surface runoff soil measurement measures.

2.5. Model Validation and Evaluation Methods

The AquaCrop model was used to simulate the canopy coverage, aboveground biomass, yield of drip irrigation maize, and soil water content. The results were fitted with the measured values of the experimental data from 2019 to 2020. The model results were verified by root-mean-square error (RMSE), simulation error or deviation percentage (Pe), and determination coefficient (R^2). The closer the RMSE to 0, the better the model performance. Pe is used to evaluate the deviation between the observed and simulated yield and the observed value. If Pe is close to 0, the model performance is better. When R^2 is close to 1, the simulation performance is good [44]. When R^2 is greater than 0.5, the simulation results are considered acceptable [45–48]. According to studies by Zheng et al. (2013) [49] and Wang et al. (2014) [43], the relative yield (Y_{rel}) and relative water use efficiency (WUE_{rel}) can be used to select the appropriate amount of irrigation related to the high yield and water use efficiency demand under each conditioner treatment. The calculation formula is as follows:

$$RMSE = \sqrt{\frac{1}{n}\sum_{i=1}^{n} (S_i - O_i)^2} \tag{9}$$

$$P_e = \frac{(S_i - O_i)}{O_i} \times 100 \tag{10}$$

$$R^2 = \left(\frac{\sum_{i=1}^{n} (O_i - \overline{O})(S_i - \overline{S})}{\sqrt{\sum_{i=1}^{n} (O_i - \overline{O})^2 \sum_{i=1}^{n} (S_i - \overline{S})^2}}\right)^2 \tag{11}$$

$$Y_{rel} = \frac{Y}{Y_m} \tag{12}$$

$$WUE_{rel} = \frac{WUE}{WUE_m} \tag{13}$$

where O_i is the observed value, S_i is the simulated value and $\overline{O}$ is the average of the measured values, $\overline{S}$ is the average value of simulated values, Y is the final yield under simulation, Y_m is the maximum simulated final yield in the scenario simulation, WUE is the water use efficiency under simulation, and WUE_m is the maximum water use efficiency in the scenario simulation.

2.6. Scenario Simulation of Amount of Irrigation Design

In order to further explore the reasonable amount of irrigation under different soil conditioner dosages in coastal saline–alkali areas, the AquaCrop model was used for scenario simulations of different amounts. Four levels of irrigation were designed: 30 mm, 60 mm, 90 mm, and 120 mm, based on full irrigation. Four levels of HA dosages were designed: 5 g/m^2 (H1), 15 g/m^2 (H2), 25 g/m^2 (H3), and 35 g/m^2 (H4). Four levels of CMC dosages were designed: 1 g/m^2 (C1), 2 g/m^2 (C2), 3 g/m^2 (C3), and 5 g/m^2 (C4). A total of 36 simulation programs were designed, as detailed in Table 4.

Table 4. Simulation programs of AquaCrop.

SPS	SCS	IA (mm)	SPS	SCS	IA (mm)	SPS	SCS	IA (mm)	SPS	SCS	IA (mm)
SP1	CK	30	SP10	CK	60	SP19	CK	90	SP28	CK	120
SP2	H1	30	SP11	H1	60	SP20	H1	90	SP29	H1	120
SP3	H2	30	SP12	H2	60	SP21	H2	90	SP30	H2	120
SP4	H3	30	SP13	H3	60	SP22	H3	90	SP31	H3	120
SP5	H4	30	SP14	H4	60	SP23	H4	90	SP32	H4	120
SP6	C1	30	SP15	C1	60	SP24	C1	90	SP33	C1	120
SP7	C2	30	SP16	C2	60	SP25	C2	90	SP34	C2	120
SP8	C3	30	SP17	C3	60	SP26	C3	90	SP35	C3	120
SP9	C4	30	SP18	C4	60	SP27	C4	90	SP36	C4	120

SPS is the simulation program, SCS is the soil conditioner, and IA is the amount of irrigation.

3. Results

3.1. AquaCrop Model Calibration

According to the maize parameters in the model manual recommended by Raes [50], the parameters in the AquaCrop model were calibrated using the measured data in 2019. The main crop parameters in the model are shown in Table 5. The CC_0 and CCx of maize were 1.50% and 90%, respectively. According to the change in canopy coverage in the maize growth cycle, the estimated CGC and CDC were 15.3% and 11%, respectively, which were higher than the 10.4% of CGC and 8.0% of CDC, respectively, the values recommended by the model manual.

Table 5. Calibration results of AquaCrop model crop parameters.

Treatment	CC RMSE (%)	Aboveground Biomass Pe (%)	Yield Pe (%)
CK	11.5	−0.756	9.852
H1	11.3	3.721	2.117
H2	12.1	−0.450	0.922
H3	11.3	−5.624	−4.024
H4	12.7	−8.508	−7.404
C1	9.5	5.362	13.018
C2	8.9	3.944	13.100
C3	9.2	3.438	11.302
C4	8.9	1.477	11.790

WP^* is one of the important crop production parameters in AquaCrop. For a given crop variety, this parameter is usually constant. In order to improve the simulation accuracy, the WP^* was fixed at 17 g/m^2 in this study, which was consistent with the maize parameter recommended by the model, within the range of 16.9–50.6 g/m^2 recommended by the model manual. The HI_0 was fixed at 36%, within the range of 24–72% recommended by the model manual. In the salt stress module, the lower limit of the influence threshold of salt on maize growth was 2 dS/m, and the upper limit of the influence threshold of salt on maize growth was 15 dS/m, which were in the ranges of 1–3 dS/m and 5–15 dS/m recommended by the model manual. Other parameters (such as the upper limit of water stress on canopy, substrate temperature, etc.) were consistent with the parameters recommended by the model manual. The calibration results (Table 5) showed that the crop parameters in the model were well adjusted using the measured crop canopy coverage, aboveground biomass, yield, and other data in 2019. The RMSE of canopy coverage was less than 12.7, aboveground biomass was $-8.508 < \text{Pe} < 5.362$, and yield was $-7.404 < \text{Pe} < 13.100$, indicating that the crop parameters in the model were well adjusted.

3.2. AquaCrop Model Validation

3.2.1. Canopy Coverage

The model was verified by CC in 2020 and 2021, so as to determine the leaf development and simulate the CC curve. The measured and simulated canopy coverage processed annually are shown in Figure 2. The CC was low 20 days after sowing and then entered a rapid development stage. The CC reached the maximum and tended to be stable 50 d after sowing, and began to decline at 85 d after sowing. Compared with no soil conditioner (CK), the RMSE and Pe values of the HA treatments were smaller, whereas the RMSE and Pe values of the CMC treatments were larger, indicating that the simulation effect of the model on CC was better when HA was applied and worse when CMC was applied. These differences could be attributed to the model failing to consider the positive effects of amendments on soil temperature and salinity. Simulations of canopy growth under water stress showed that canopy coverage was poor.

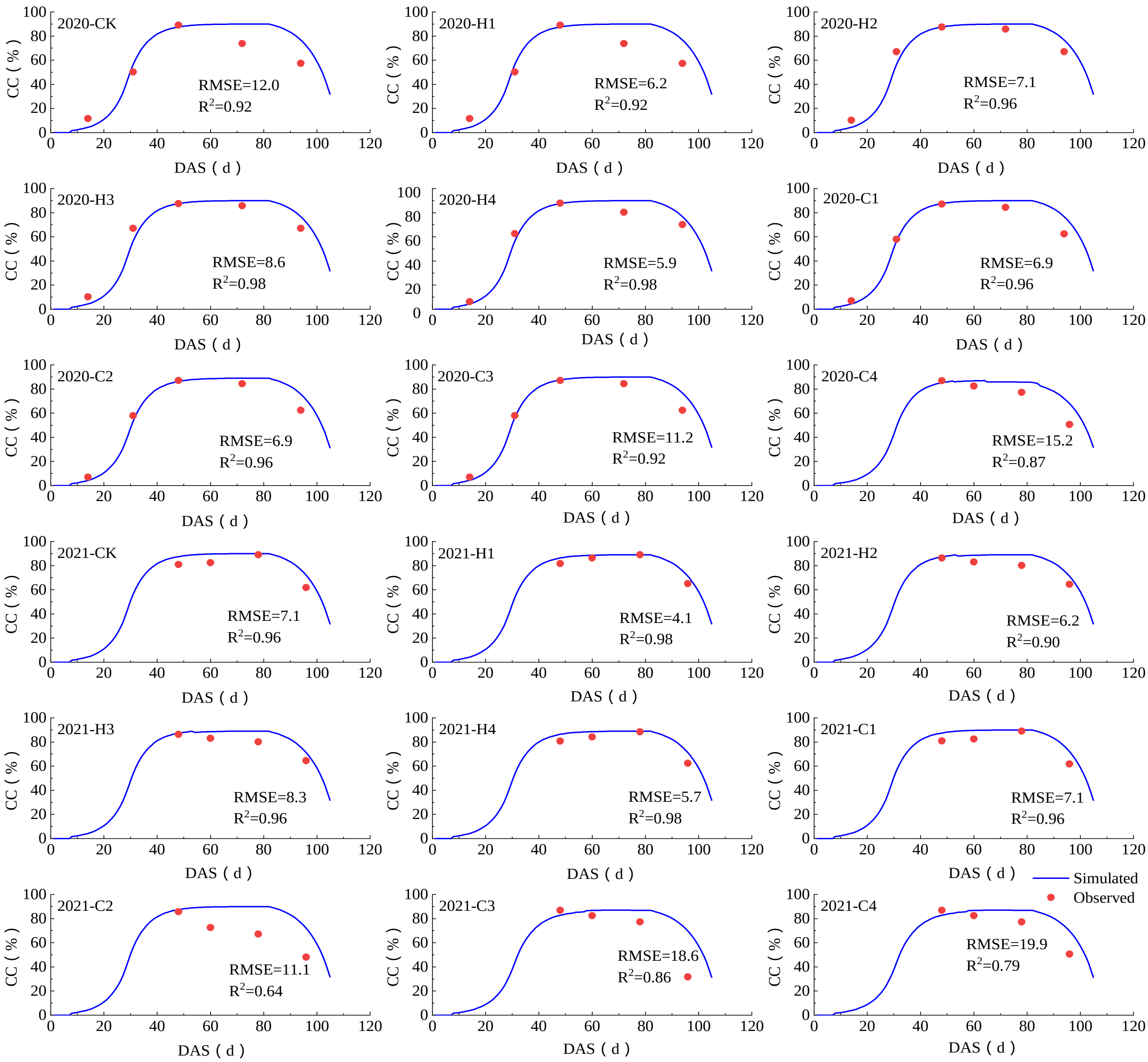

Figure 2. Simulated and observed canopy coverage curves of maize under all treatments in 2020–2021. CC is the canopy coverage of maize, and DAS is the days after sowing.

3.2.2. Aboveground Biomass

Simulations of aboveground biomass during the validation period were analyzed. As shown in Figure 3, the model could accurately simulate growth trends in the aboveground biomass of each treatment, although most of the simulated values were slightly lower than the observed values. Comparing irrigation treatments showed that the simulation results for the final aboveground biomass under HA treatments were better than those under CMC treatments.

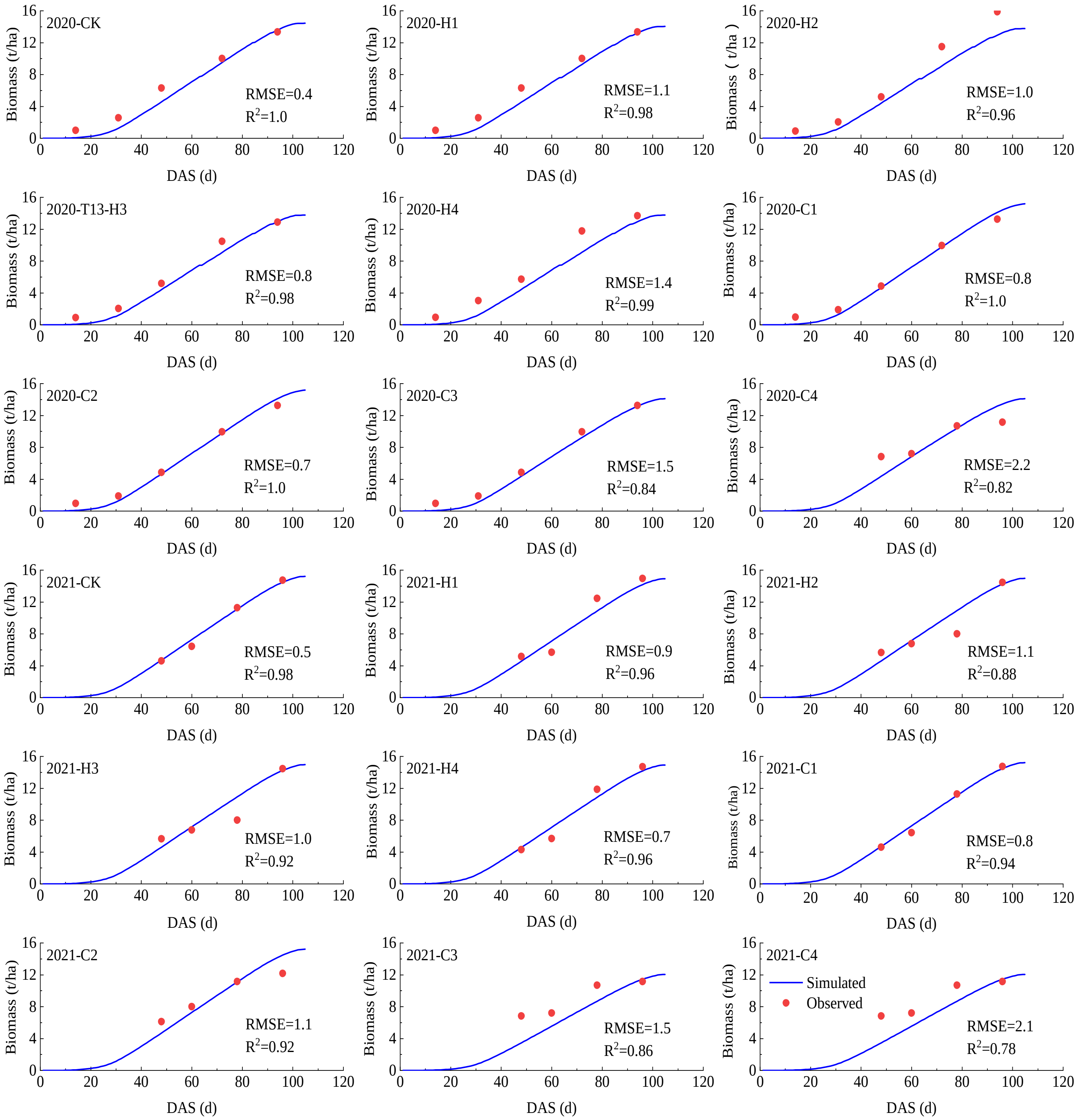

Figure 3. Simulated and observed biomass curves of maize under all treatments in 2020–2021. DAS is the days after sowing.

3.2.3. Soil Water Storage

The AquaCrop model is a water-driven model. It is very important to evaluate the simulation ability of soil water content (SWS). All of the data in the two validation growing seasons (2020–2021) were predicted by 30 cm soil profile SWS. The measured soil water content under each treatment in 2020–2021 was compared with the simulated soil water content, as shown in Figure 4. The variation trend in SWS values, simulated and observed by each treatment model, was basically the same. However, there was a great difference between the simulated value and the observed value under the treatment of soil conditioner. In 2020, the R^2 of SWS under modifier treatment was $\leq$0.88, and the RMSE range was 4.7–19.8. In 2021, the R^2 of SWS under modifier treatment was $\leq$1.00, and the RMSE range was 3.1–15.4. These results showed that the simulation effect of the model on the soil water storage (SWS) under modifier conditions was poor.

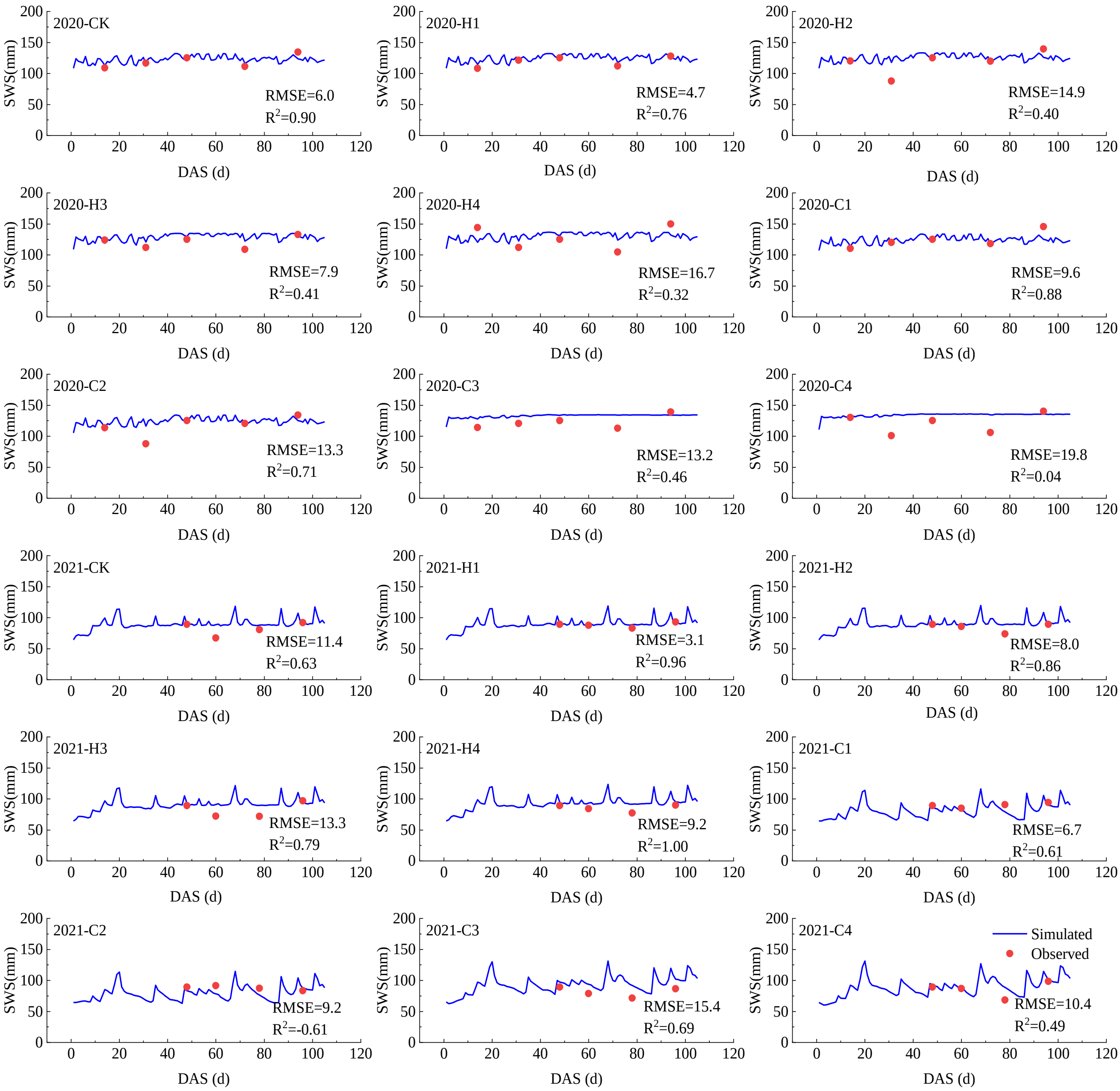

Figure 4. Simulation and observation of soil water storage under all treatments during 2020–2021. SWS is the soil water storage and DAS is the days after sowing.

3.2.4. Yield

Figure 5 shows the simulated and measured maize yield in 2020–2021. The model had a good simulation effect on maize yield from 2020 to 2021. The Pe of each treatment ranged from 3.64% to 17.99%. The simulation effects of HA treatments were better than that of CMC treatment. In 2021, the Pe between the simulated and measured yield of high gradient CMC (C3 and C4) exceeded 10.62%, and the model underestimated the yield of maize. The results showed that the AquaCrop model was sufficient to predict maize yield under modifier conditions.

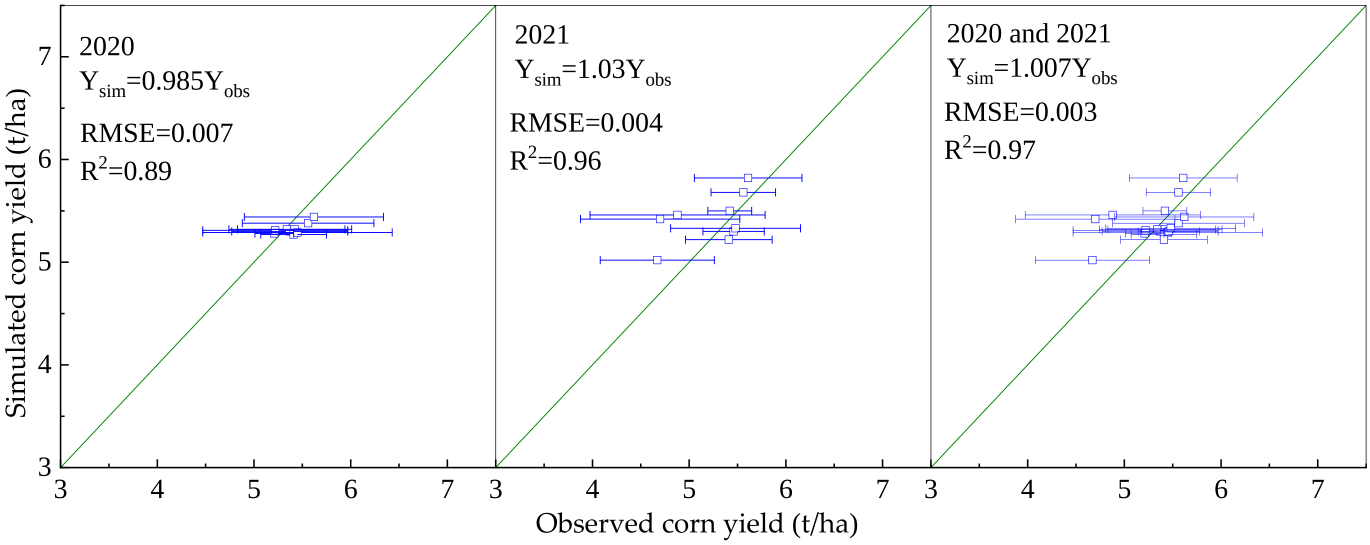

Figure 5. Observed and simulated maize yields for 2020 and 2021 seasons. The error bars represent standard deviations.

3.3. Optimization of Amount of Irrigation under Soil Conditioners

According to the needs of high yield and water-use efficiency, the optimized amount of irrigation could be determined. Through the maximum simulated yield and WUE, the simulated yield and water-use efficiency under each soil conditioner treatment scenario were normalized to find the optimized amount of irrigation. The relationship between Y_{rel} and WUE_{rel} could also be described by the quadratic function of the amount of irrigation. Therefore, a reasonable amount of irrigation could be determined according to the response function of relative yield and relative water-use efficiency to the amount of irrigation. For example, when the initial salinity was 10 dS/m, the optimized amount of irrigation without soil conditioner treatment was 52 mm, as shown in Figure 6. The simulation results of other scenarios under each soil conditioner treatment could be obtained from the two response functions of relative yield and relative water use efficiency (Table 6). The results showed that the optimized amount of irrigation of maize for HA and CMC treatments were 47.0–65.9 mm and 61.0–92.4 mm, respectively, in the coastal saline–alkali area.

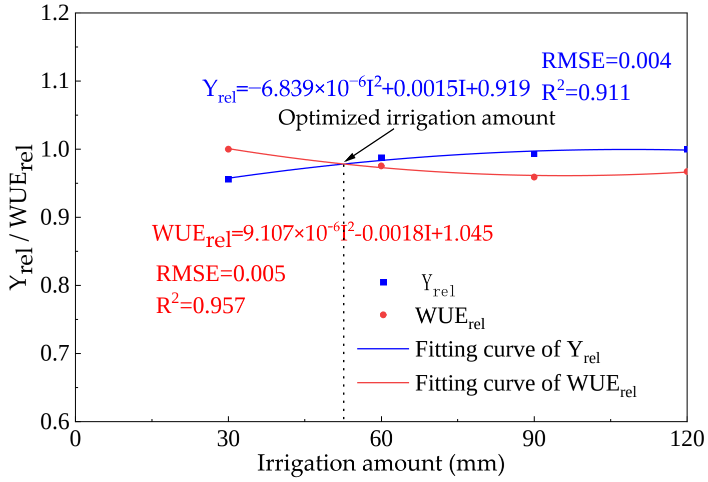

Figure 6. Optimized irrigation amount under the control treatment (CK).

Table 6. The optimized levels of irrigation under different soil conditioner treatments.

Treatment	Salinity (dS/m)	Y_m (t/ha)	ET_m (mm)	WUE_m (kg/m)	Optimizations			
					IA′ (mm)	ET′ (mm)	WUE′ (kg/m)	Y′ (t/ha)
CK	10	4.671	395.8	1.22	52.7	387.2	1.19	4.569
H1	10	4.666	396.2	1.24	47.0	388.7	1.22	4.578
H2	10	4.673	396.6	1.24	53.4	388.8	1.22	4.582
H3	10	4.664	394.1	1.25	65.9	385.2	1.22	4.558
H4	10	4.664	394.4	1.26	52.2	388.1	1.24	4.589
C1	10	4.514	355.5	1.30	82.1	350.7	1.28	4.536
C2	10	4.649	361.6	1.30	92.4	357.9	1.29	4.601
C3	10	4.705	372.1	1.32	61.0	367.8	1.30	4.651
C4	10	4.692	370.1	1.31	73.7	364.6	1.29	4.623

Y_m, ET_m, and WUE_m are the simulated yield, evapotranspiration, and water use efficiency of maize, respectively. IA′, ET′, WUE′, and Y′ are the optimized amount of irrigation, evapotranspiration, water use efficiency, and yield of maize.

4. Discussion

The AquaCrop model was used to simulate the growth and yield of maize in coastal saline–alkali areas, and the model parameters were corrected and verified through three years of field test data. The results showed that the model could accurately simulate the canopy coverage of maize from 2019 to 2021, although the content of CMC was greater than 2 g/m^2. The $R^2 \geq$ (0.87) was relatively high, whereas the RMSE $\leq$ (15.2%) was relatively low. When the dosage of CMC applied was greater than 2 g/m^2, the simulation effect of this model on canopy coverage was poor, which might cause soil hardening with the treatment of high concentrations of CMC, thus affecting crop growth and development [51]. Heng et al. [52] pointed out that the simulation effect of this model under irrigation treatment was significantly better than that under water stress. Sandhu and Irmak [53] also found that the model had limitations in simulating canopy coverage under water stress.

The three-year simulation results of aboveground biomass showed that the model could accurately simulate growth trends in the aboveground biomass of each treatment, although the simulated values of most treatments were slightly lower than the observed values. The simulation effect of HA treatment was better than that of CMC treatment. Only the influence of a modifier on soil structure was considered; therefore, the simulated value was lower than the measured value. Zhang et al. [54] found that HA could not only affect soil structure, but also improve chlorophyll content and nitrate reductase activity, which was conducive to the accumulation of crop dry matter. Moreover, the model simply used crop water productivity to simulate the actual aboveground biomass, and calculated the aboveground biomass according to *WP** and Tr. Therefore, the difference might be due to a lower *WP** or lower simulated Tr (unadjusted crop Tr coefficient), or the underestimation of root absorption.

During the validation period from 2020 to 2021, the AquaCrop model predicted the soil water content of 30 cm soil profiles, which showed that the simulated value of SWS was overestimated in the growth stage of maize. These overestimations in SWS might also be due to the unadjusted crop coefficient of Tr in the model. Similar differences were also found in the study on the application of the AquaCrop model in maize [42,55]. Paredes et al. [55] also reported that the distribution of ET in aquatic crops needed to be modified according to the FAO56 method. Another reason for these differences might be that the simulation of root development was inaccurate based on the simple assumption in the model that root depth growth was expressed as an empirical formula related to time and maximum effective root depth. Although the effect of water stress on root development was considered in root development, due to the high variability in maize root density, it might not actually reflect the complex situation of drip irrigation under film. Ning et al. [56] found that some parameters related to root distribution, such as root density or specific root length, could be added to calculate the root distribution of aquatic crops. The overestimation of SWS might also be related to the capillary rise of groundwater.

From 2019 to 2021, the simulated yield of each modifier treatment under full irrigation was underestimated, and the absolute value of the maximum deviation of each treatment exceeded 13%, mainly because the simulated aboveground biomass was low, so the simulated yield obtained was lower than the measured value. The simulation effects of maize yield under the treatments of soil conditioner were worse than those without modifiers, mainly because the application of HA and CMC was conducive to increasing crop root activity, enhancing crop absorption and the utilization of nutrients, and maintaining vigorous crop metabolism [24,57]. Therefore, it was not sufficient to simply consider the change in soil structure by modifiers to simulate the final yield of the crops. In order to improve the simulation accuracy under the condition of modifier, it is suggested to add a parameter to the simulation under modifier conditions to express the promoting effect of the modifier on crop growth. According to the scenario simulation results, under moderate salt stress, the optimized levels of irrigation of HA and CMC were 47.0–65.9 mm and 61.0–92. 4 mm, respectively.

5. Conclusions

The AquaCrop model was used to simulate the performance of maize growth under different modifier types and application rates based on three-year field test data in coastal saline–alkali areas of Shandong Province, China. The results showed that the AquaCrop model could accurately simulate canopy coverage, aboveground biomass, and the yield of maize under drip irrigation, considering the effects of amendments on soil field capacity, saturated water content, permanent wilting point, and saturated hydraulic conductivity. Modifiers and their dosages had important effects on crop evapotranspiration, water use efficiency, and yield. According to the local maize planting and irrigation system, based on the requirements of high yield and water use efficiency, it was recommended that the amount of irrigation of humic acid (HA) treatment should be 47.0–65.9 mm and that of sodium carboxymethyl cellulose (CMC) treatment should be 61.0–92.4 mm. In addition, the amount of irrigation depends on soil water content and salt content during sowing. It is suggested that the amount of irrigation should be increased when sowing under conditions of high soil water content and low salt content. This suggestion can provide reference for the irrigation management of HA and CMC in coastal saline–alkali areas.

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