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Parameterization of the AquaCrop model for full and deficit irrigated maize for seed production in arid Northwest China

Hui Ran[a,b], Shaozhong Kang[a,*], Fusheng Li[c], Taisheng Du[a], Ling Tong[a], Sien Li[a], Risheng Ding[a], Xiaotao Zhang[a]

[a] Center for Agricultural Water Research in China, China Agricultural University, Beijing 100083, China
[b] Key Laboratory of Agricultural Soil and Water Engineering in Arid and Semiarid Areas, Ministry of Education, Northwest A&F University, Yangling 712100, China
[c] College of Agriculture, Guangxi University, Nanning, Guangxi 530005, China

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ABSTRACT

A crop model is a powerful tool for developing an irrigation schedule and simulating crop yield. In this study, both an AquaCrop model using recommended default parameters and a parameterized AquaCrop model were used to simulate the growth of maize for seed production under plastic film-mulch. The model variables that were parameterized include canopy cover (CC), aboveground biomass, yield (Y) and soil water content (SWC). Data from field experiments, which included 23 irrigation treatments on four varieties of maize for seed production, were collected in an arid region of Northwest China from 2012 to 2015. The results from both the default AquaCrop model and the parameterized model were compared with the field data. The parameterized model performed much better than the default model. Overall it predicted CC well for most irrigation treatments, with determination coefficient (R^2) and normalized root mean square error (NRMSE) of 0.818 and 19.3%, respectively. However, the model was rather sensitive to water stress during the vegetative stage and insensitive to water stress during the senescence stage, resulting in underestimation and overestimation of CC during these stages. As for biomass accumulation process, R^2 and NRMSE were 0.929 and 19.1% for all treatments, respectively. The parameterized model estimated biomass accurately in the early and middle stages of growth, but generally overestimated biomass at the mature stage, giving a slightly decreased accuracy of final biomass (B) simulation. The parameterized AquaCrop model simulated B and Y values with errors of less than 5% of measured values for 4 and 7 treatments out of 23 treatments, respectively. There were of less than 15% for 12 and 13 treatments out of 23, of less than 30% for 19 and 16 treatments out of 23, and greater than 30% for 4 and 7 treatments out of 23, respectively. The model gave reasonable estimates of SWC with R^2 and NRMSE of 0.736 and 15.2%, respectively, but tended to overestimate it for most irrigation treatments. Simulation of the variation of WP^* in the growth period, and the differences of HI under different water stress conditions, might be improved in the AquaCrop model.

1. Introduction

Maize for seed production is different from maize grown for other purposes (such as silage or cereal). It has a smaller leaf area, less biomass, lower yield, and consists of separate male and female plants. The tassel of the female parent is removed before flowering, and the ear of the female parent receives the pollen of the male parent to produce the final hybrid seed yield. Hexi Corridor in Northwest China is an important area for maize for seed production, where the planting area is 100,000 ha, which accounts for 39.3% of total area of this crop in China (255,000 ha). The yield of maize for seed production is 580,000 tons, which accounts for 42.6% of the total yield of this crop in China in 2013 (Wang et al., 2013a).

Hexi Corridor is located in a typical arid climate zone, with annual rainfall < 200 mm. There is a serious shortage of water, and agriculture depends heavily on irrigation (Du et al., 2015; Kang et al., 2017). Due to the scarcity of water, the crop often suffers water stress and its yield decreases. An understanding of the effects of different degrees of water stress on maize for seed production is very important for optimal irrigation management and crop production. Field experiments are often time-consuming and costly, so crop models can greatly help to improve crop management (Rötter et al., 2012; Mabhaudhi et al., 2014).

Modelling crop growth can provide a powerful tool for evaluating the effects of environmental factors on crops (Steduto et al., 2009;

* Corresponding author.
E-mail address: kangsz@cau.edu.cn (S. Kang).

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Rötter et al., 2015). There are many widely used crop models, such as WOFOST (Diepen et al., 1989), EPIC (Sharpley and Williams, 1990), CropSyst (Stöckle et al., 2003), DSSAT (Jones et al., 2003), APSIM (Keating et al., 2003) and WAVES (Kang et al., 2003). However, these models are complex; they require many parameters that are often difficult to quantify and can be time-consuming to obtain. To overcome these obstacles, FAO developed the AquaCrop model to be accurate, simple, robust, and easy to use (Steduto et al., 2009; Raes et al., 2009; Hsiao et al., 2009). The model is now used worldwide and it is an important tool for managing and forecasting crop production. It has been successfully used to simulate the development of many crops: maize (Hsiao et al., 2009; Stricevic et al., 2011; Abedinpour et al., 2012; Nyakudya and Stroosnijder, 2014; Paredes et al., 2014), wheat (Andarzian et al., 2011; Mkhabela and Bullock, 2012; Wang et al., 2013b; Iqbal et al., 2014; Toumi et al., 2016), cotton (Garcia-Vila et al., 2009; Linker et al., 2016), rice (Maniruzzaman et al., 2015), sunflowers (Todorovic et al., 2009; Stricevic et al., 2011), barley (Araya et al., 2010a), quinoa (Geerts et al., 2009), teff (Araya et al., 2010b), taro (Mabhaudhi et al., 2014), and others. However, Heng et al. (2009) and Katerji et al. (2013) showed that although AquaCrop can accurately estimate the canopy coverage, biomass, and yield of maize under full irrigation and mild water stress conditions, the accuracy of the simulation is poor when there are severe water deficit conditions, especially when the water deficit occurs in the senescence period. It has been shown that AquaCrop can accurately simulate change in soil water content under full irrigation conditions, but generally overestimates soil water content for deficit irrigation applications, especially for cotton (Farahani et al., 2009). Hsiao et al. (2009) have suggested that AquaCrop should be further validated for different soils, crops, and climates worldwide.

To give good simulation results for crop characteristics such as biomass and yield, the parameters of an AquaCrop model must be calibrated. There is no literature concerning the parameterization of an AquaCrop model for maize that is grown as a seed crop, and it is not clear that the default parameters for other maize crops can be used unaltered for such a model, especially with deficit irrigation. In addition, there has been little research into the use of AquaCrop in the inland arid climate of Northwest China. Thus, the objective of this study is to parameterize an AquaCrop model on maize for seed production in an arid region of Northwest China under both full irrigation and deficit irrigation so that the model provides accurate yield forecasts under different irrigation conditions.

2. Materials and methods

2.1. Experimental site and its description

Field experiments were conducted at the Shiyanghe Experimental Station for Water-Saving in Agriculture and Ecology, part of the China Agricultural University, located in Wuwei City, Gansu Province, Northwest China (37°52′ N, 102°50′ E, elevation 1581 m), from 2012 to 2015. The experimental site is located in an arid inland climate zone with abundant light and heat, but with a water scarcity (Li et al., 2015). The soil has a light sandy loam texture, with mean soil dry bulk density of 1.4 g cm^{-3}, mean saturated water content of 0.41 cm^3 cm^{-3}, mean field capacity (FC) of 0.30 cm^3 cm^{-3}, mean permanent wilting point of 0.10 cm^3 cm^{-3}, and mean saturated hydraulic conductivity of 500 mm d^{-1} for the 0–100 cm soil layer.

2.2. Experimental methods

To generate values for the conservative crop parameters of AquaCrop, field data were collected over four years (2012–2015) for crops of different maize varieties under different irrigation treatments.

In 2012, the following experiment was conducted. Six experimental irrigation treatments were designed to study the responses of maize for seed production to deficit irrigation at different growth stages. Each treatment was classified in one of two groups: full irrigation (CK) and deficit irrigation (DI). In CK sufficient water was applied to reach 100% crop evapotranspiration (ET) during the whole growth stage of the maize. In DI a planting was deficit irrigated at one of a number different growth stages with a limited amount of water so that ET over the growth stage was 55%; the plants were fully irrigated (i.e. ET was 100%) during the other stages. The five growth stages were the seedling stage (SD), the jointing stage (JD), the heading stage (HD), the filling stage (FD), and the maturing stage (MD). The maize for seed production (*Zea mays* L., cultivar Zhengdan 958) was sown on April 19, 2012 and harvested on September 20, 2012.

In 2013, the following experiment was conducted. Three irrigation treatments (W1, W2, and W3) were designed to study the responses of maize for seed production to different degrees of water stress during the growth period. For each treatment, irrigation water was supplied until the soil water content reached 65–70% (W1), 55–60% (W2), or 45–50% (W3) of field capacity (FC). The upper irrigation limit was the field capacity. The maize for seed production (*Zea mays* L., cultivar Funong 340) was sown on April 20, 2013 and harvested on September 11, 2013.

In 2014, two experiments were conducted. The first of them was a repeat of the 2013 experiment. The second experiment, consisting of four irrigation treatments (CK, IV3, IV2, and IR2), was designed to study the responses of maize for seed production to irrigation at different times. In treatment CK, full irrigation, the crop was irrigated four times during the whole crop season. In treatment IV3 the crop was irrigated three times during the vegetative stage. In treatment IV2, the crop was irrigated twice during the vegetative stage. In treatment IR2 the crop was irrigated twice during the reproductive stage. For all treatments, each irrigation supplied 120 mm water. Maize for seed production (*Zea mays* L., cultivar Funong 963) was used in both experiments and was sown on April 15, 2014 and harvested on September 20, 2014.

In 2015, the following experiment was conducted. Seven irrigation treatments (CK, IV3, IR3, IV2, IR2, IV1, and IR1) were designed to study the responses of maize for seed production to different irrigation times. In treatment CK, full irrigation, there were five irrigations during the whole growing season. In treatment IV3 there were three irrigations during the vegetative stage. In treatment IR3 there were three irrigations during the reproductive stage. In treatment IV2 there were two irrigations during the vegetative stage. In treatment IR2 there were two irrigations during the reproductive stage. In treatment IV1 there was one irrigation during the vegetative stage. In treatment IR1 there was one irrigation during the reproductive stage. In every treatment, each irrigation supplied 120 mm water. Maize for seed production (*Zea mays* L., cultivar Funong 588) was sown on April 15, 2015 and harvested on September 16, 2015.

Every experiment was conducted in a randomized complete block design, and each treatment had three replicates. The maize for seed production was sown alternating one row of male plants with five rows of female plants under plastic film mulch, with plant spacing of 0.25 m and row spacing of 0.4 m. Nitrogen (N), phosphorus (P_2O_5) and potassium (K_2O) fertilizers were applied at 500 kg ha^{-1}, 240 kg ha^{-1} and 50 kg ha^{-1} respectively, according to average long-term fertilization data, in each of the four years. Except for irrigation, other farming management measures were similar for all treatments. Each plot field had an area of 86.8 m^2 (12.4 m × 7 m) during the five one-year experiments. The plots were separated by ridges (0.3 m wide and 0.5 m high), and 1 m wide strips were left around the inside of each plot for protection. Uniform border irrigation was adopted as the irrigation method. Irrigation pipelines were buried in the ridges. For each plot, the main pipes were equipped with a water meter to measure the irrigation amount, and a water outlet was installed at the head. The irrigation time and depth data for each treatment are shown in Table 1.

Table 1
Irrigation treatments and schedules during the growing season of maize for seed production from 2012 to 2015.

2012 (Sown on April 19)							2013 (Sown on April 20)				2014 (Sown on April 15)								2015 (Sown on April 15)							
	CK[a]	SD	JD	HD	FD	MD		W1	W2	W3		W1	W2	W3	CK	IV3	IR2	IV2		CK	IV3	IR3	IV2	IR2	IV1	IR1
DAP	Irrigation depth (mm)						DAP	Irrigation depth (mm)			DAP	Irrigation depth (mm)							DAP	Irrigation depth (mm)						
49	68	37	68	68	68	68	53	63			60	81			105	90		90	53	90	90		90			
66	105	105	58	105	105	105	86	99	128		89	81	81		120	120		120	76	120	120		120		120	
85	120	120	120	66	120	120	99			48	108	81		115	120	120	120		96	120	120	120				
119	112	112	112	112	62	112	106	62		84	123		98						106							120
137	90	90	90	90	90	50	123	115	52		129	31							114	120		120		120		
							134		58		135				120		120		133	120		120		120		

[a] Irrigation treatments. CK, SD, JD, HD, FD and MD in 2012 mean full irrigation, deficit irrigation at the seedling stage, the jointing stage, the heading stage, the filling stage, and the maturing stage, respectively; W1, W2 and W3 in 2013 and 2014 mean irrigation water was supplied until the soil watercontent reached 65–70%, 55–60%, 45–50% of field capacity, respectively; CK, IV3, IV2 and IR2 in 2014 and 2015 mean full irrigation, irrigation three times at the vegetative stage, irrigation two times at the vegetative stage, irrigation two times at the reproductive stage. IR3, IV1 and IR1 in 2015 mean irrigation three times at the reproductive stage, irrigation once at the vegetative stage and irrigation once at the reproductive stage. DAP is days after planting.

2.3. Measurements

2.3.1. Meteorological data

Meteorological data were continuously measured during the experimental period by a standard automatic weather station (Hobo, Onset Computer Corp., USA) located near the experimental field. The data were taken every 5 s, and 15-min averages were recorded by a data logger. The daily reference crop evapotranspiration (ET_0) was calculated using the FAO Penman–Monteith method (Allen et al., 1998). The daily maximum and minimum temperatures, solar radiation, minimum relative humidity, precipitation and ET_0 for each growing season are shown in Fig. 1.

2.3.2. Canopy cover

Canopy cover (CC) was derived from the leaf area index (LAI) by the following empirical equation, given by Hsiao et al. (2009):

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

Nine female plants from each treatment group were randomly chosen to measure the green leaf length and maximum leaf width every 7 d to 10 d over the growing period. Leaf area was calculated by summing (leaf length × maximum leaf width) and multiplying by a factor of 0.7; this value was derived by linear regression through the origin between the calculated and actual values ($R^2 = 0.998$). The actual values were measured by an AM300 leaf area meter (ADC BioScientific Ltd., UK). The leaf area index (LAI) was taken to be leaf area per unit of area.

2.3.3. Soil water content

Gravimetric soil water content was measured at depths of 10 cm, 20 cm, 40 cm, 60 cm, 80 cm, and 100 cm with two replicates in each plot. The mean soil water content in the soil profile was taken to be the average of the soil water content measurements in the 0–100 cm layer. The initial values of soil water content for each plot before sowing were measured each year. Soil water content was also measured before and after each irrigation for all the treatments from 2013 to 2015.

2.3.4. Biomass, yield and harvest index

Nine female plants from each treatment were harvested at ground level every 10 d to 20 d to measure the aboveground biomass. All the harvested plants were oven dried at 105 °C for 30 min, and then dried at 70 °C to obtain the constant dry weight. At the end of each growth period, sixty female plants were randomly selected from each treatment and harvested for seed yield. Grains were first oven dried at 105 °C for 30 min, and then dried to constant mass at 70 °C. The final seed yield was normalized on the basis of 13% moisture content for comparison between treatments. The harvest index was defined as yield divided by final biomass.

2.4. Description of the AquaCrop model

Yield (Y) is estimated from the final biomass and the harvest index in AquaCrop (Steduto et al., 2009; Raes et al., 2009). The equation is:

$$Y = f_{HI} HI_0 B \quad (2)$$

where: f_{HI} is the adjustment factor that accounts for the effects of water stress before yield formation, failure of pollination, and water stress during yield formation; HI_0 is the reference harvest index; and B is the final biomass.

The final biomass is estimated from normalized water productivity and the sum of the ratios of the daily crop transpiration (T) to the reference evapotranspiration (ET_0):

$$B = Ks_b WP^* \sum \frac{T}{ET_0} \quad (3)$$

where Ks_b is the air temperature stress coefficient and WP^* is normalized water productivity.

Crop transpiration is calculated as:

$$T = Ks CC^* Kc_{Tr,x} ET_0 \quad (4)$$

where: Ks is the soil water stress coefficient, caused by excess water (Ks_{aer}), water shortage (Ks_{sto}), and soil salinity ($Ks_{sto,salt}$); CC^* is the adjusted canopy cover to account for inter-row microadvectivity and sheltering effects due to partial canopy cover; $Kc_{Tr,x}$ is the coefficient for maximum crop transpiration under conditions of well-watered soil and completely covered canopy; and ET_0 is reference evapotranspiration calculated using the FAO Penman–Monteith method (Allen et al., 1998).

To more accurately estimate T, the canopy cover (CC) is adjusted to $CC^*$by the equation:

$$CC^* = 1.72CC - CC^2 + 0.30CC^3 \quad (5)$$

Canopy cover is a crucial component of AquaCrop as its expansion, aging, conductance, and senescence determine the transpiration amount, which in turn determines biomass. CC development is given by:

$$CC = CC_0 e^{tCGC} \text{ for } CC \le CC_x/2 \quad (6)$$

$$CC = CC_X - 0.25\frac{CC_X{}^2}{CC_0} e^{-tCGC} \text{ for } CC > CC_X/2 \quad (7)$$

where CC_0 is the initial canopy size at 90% emergence, CC_x is the maximum canopy cover, CGC is the canopy growth coefficient for optimal conditions, and t is time.

The decline in green crop canopy is given by:

$$CC = CC_X\left[1 - 0.05\left(e^{\frac{CDC}{CC_X}t} - 1\right)\right] \quad (8)$$

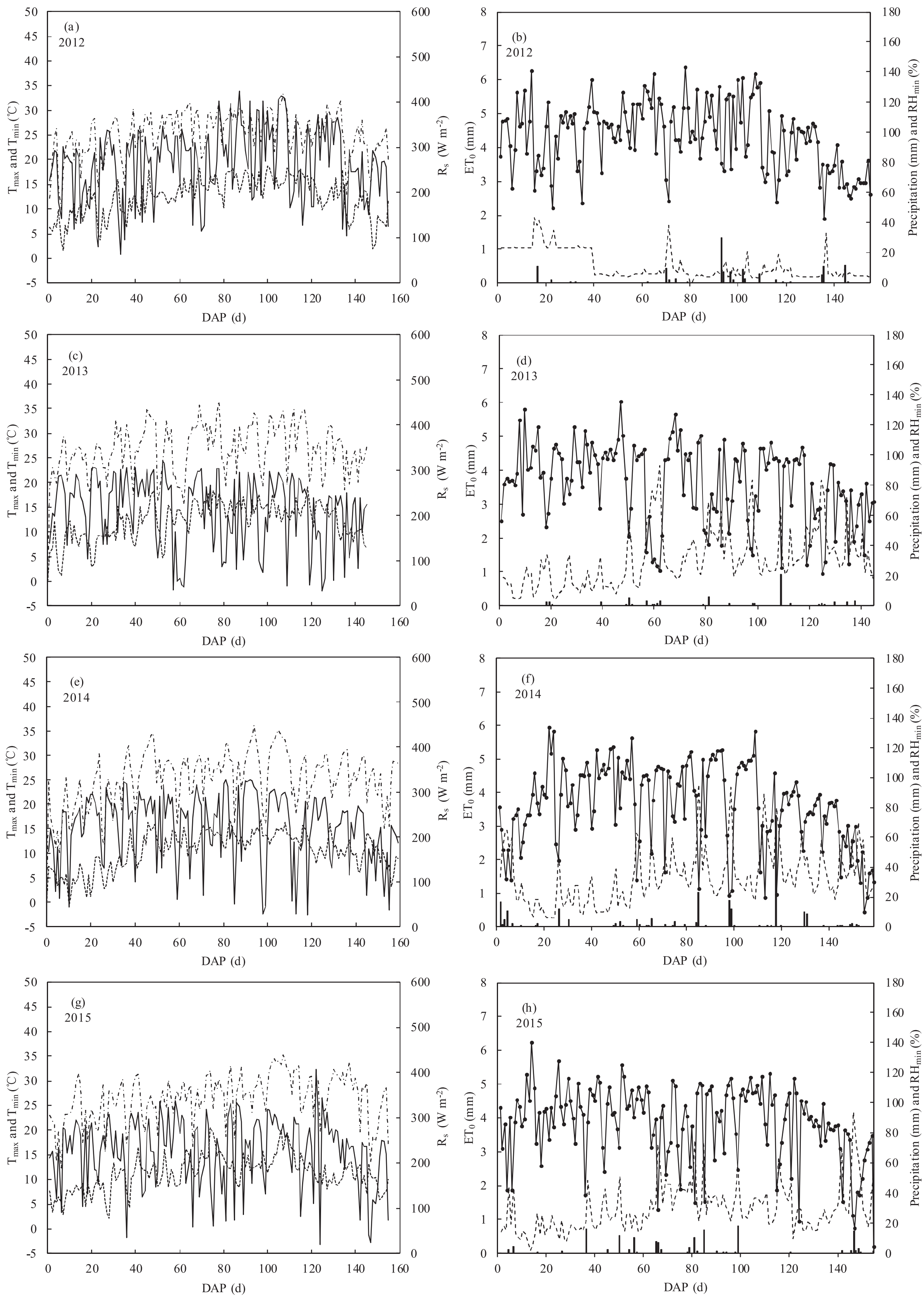

Fig. 1. Variation in daily climate data for days after planting (DAP) of maize for seed pro-duction from 2012 to 2015, including maximum (T_{max}, ———) and minimum (T_{min}, – · – · – ·) temperature, solar radiation (R_s, ——), minimum relative humid (RH_{min}, ———), precipita-tion (▌) and reference evapotranspiration (ET_0, —•—).

Table 2
Default and calibrated values of parameters of maize for seed production in the AquaCrop model.

Description and unit	Default value	Calibrated value
Base temperature, °C	8	8
Upper temperature, °C	30	30
Minimum growing degrees required for full biomass production, °C d	12	12
Canopy size of the average seedling at 90% emergence(cc_0), cm^2	6.5	6.5
Number of plants per hectare	50,000–100,000	100,000
Maximum canopy cover, %	65–99	90
Canopy growth coefficient (CGC), $(°C\ d)^{-1}$	0.012–0.013	0.0115
Canopy decline coefficient (CDC), $(°C\ d)^{-1}$	0.010	0.0052
Minimum effective rooting depth, m	0.3	0.3
Maximum effective rooting depth, m	Up to 2.80	1
Shape factor describing root zone expansion	1.3	1.3
Crop coefficient for transpiration at CC = 100% ($Kc_{Tr,x}$)	1.05	1.20
Water productivity normalized for ET_0 and CO_2 (WP^*), $g\ m^{-2}$	33.7	20.9
Reference harvest index (HI_0), %	48–52	33
Possible increase of HI due to water stress before flowering	none	none
Excess of potential fruits	small	very small
Coefficient describing positive impact of restricted vegetative growth during yield formation on HI	small	none
Coefficient describing negative impact of stomatal closure during yield formation on HI	strong	very strong
Allowable maximum increase of specified HI, %	15	15
Leaf growth threshold (p_{upper})	0.14	0.14
Leaf growth threshold (p_{lower})	0.72	0.72
Leaf growth stress coefficient curve shape	2.9	2.9
Stomatal conductance threshold (p_{upper})	0.69	0.5
Stomata stress coefficient curve shape	6.0	6.0
Senescence stress coefficient (p_{upper})	0.69	0.5
Senescence stress coefficient curve shape	2.7	2.7
Soil water depletion factor for pollination	0.8	0.75
Time from sowing to emergence, °C d	60–100	55
Time from sowing to maximum rooting depth, °C d	–	578
Time from sowing to the start of senescence, °C d	T_{SE}[a] + (1150–1500)	1243
Time from sowing to maturity, i.e. length of crop cycle, °C d	T_{SE}[a] + (1450–1850)	1549–1668
Time from sowing to flowering, °C d	T_{SE}[a] + (600–900)	788
Length of the flowering stage, °C d	150–200	210
Length of building up HI, °C d	–	711

"–" means not given.
[a] T_{SE} is the time from sowing to emergence.

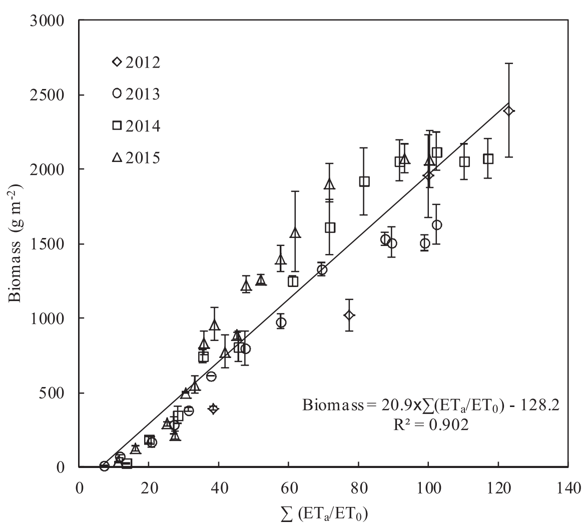

Fig. 2. Linear regression between aboveground biomass and sum of the ratios of actual evapotranspiration to reference evapotranspiration up to the time of each biomass measurement ($\Sigma ET_a/ET_0$) from 2012 to 2015.

where CDC is the canopy decline coefficient for optimal conditions.

CGC and CDC are modified by soil water stress:

$$CGC_{adj} = Ks_{exp,w} CGC \quad (9)$$

$$CDC_{adj} = (1 - Ks_{sen}{}^{8}) CDC \quad (10)$$

where CGC_{adj} is CGC adjusted for soil water stress, $Ks_{exp,w}$ is the water stress coefficient during the development stage of canopy cover, CDC_{adj} is CDC adjusted for soil water stress, and Ks_{sen} is the water stress coefficient for the acceleration of senescence. A detailed conceptual description of AquaCrop is available in Steduto et al. (2009) and Raes et al. (2009).

2.5. Parameterization of the AquaCrop model

AquaCrop has no pre-determined parameters for maize for seed production, although it has default parameters for maize. Since the objective of this study was to obtain a set of conservative parameters for maize for seed production, the approach to parameterizing the model was the same as that of Hsiao et al. (2009), in which different values of the assumed conservative parameters were used iteratively to minimize the error between the simulated and measured data. Since the varieties of maize for seed production were different between experiments, we could not use the common method of calibrating the model with one or two years of observed data and then validating the model with data observed in subsequent years. All the observed data from 2012 to 2015 were used in the parameterization, following the approach used by Hsiao et al. (2009). The advantage of this approach is that the obtained parameter values were specifically applicable to maize for seed production and could be used for the different varieties. The disadvantage is that there might have been a systematic error for a specific variety. For model simplicity and ease of usability, the phenology of maize for seed production was set to the same value for every year. We followed the process of parameterization given by Vanuytrecht et al. (2014). First, we calibrated canopy cover; second, we calibrated biomass; and third, we calibrated yield.

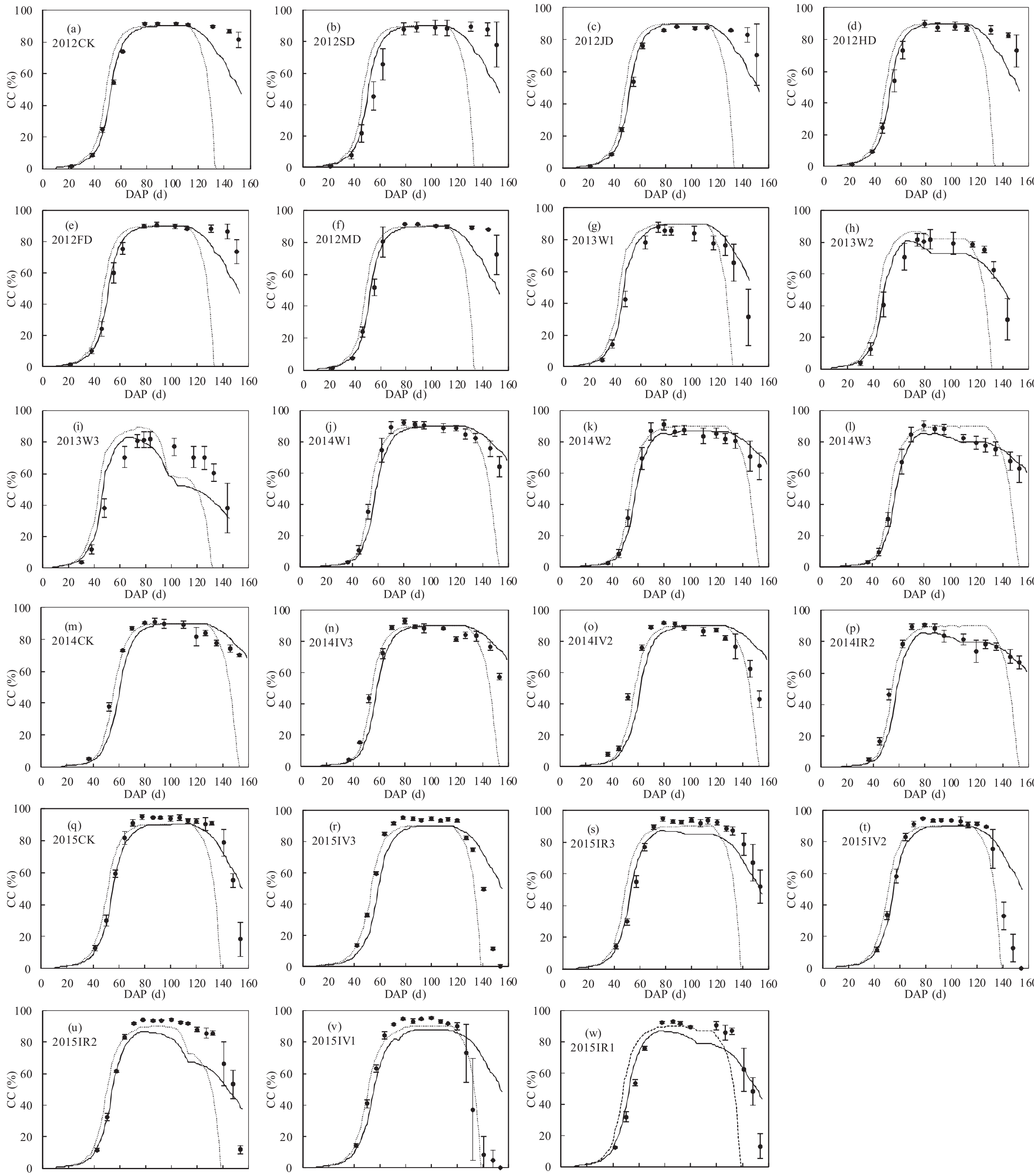

Fig. 3. Comparison of simulated canopy cover (CC) using default (……) and calibrated (——) parameters with observed values (•) of maize for seed production in an arid region of Northwest China from 2012 to 2015.

DAP is days after planting.

CK, SD, JD, HD, FD and MD in 2012 mean full irrigation, deficit irrigation at the seedling stage, the jointing stage, the heading stage, the filling stage, and the maturing stage, respectively; W1, W2 and W3 in 2013 and 2014 mean irrigation water was supplied until the soil water content reached 65–70%, 55–60%, 45–50% of field capacity, respectively;

CK, IV3, IV2 and IR2 in 2014 and 2015 mean full irrigation, irrigation three times at the vegetative stage, irrigation two times at the vegetative stage, irrigation two times at the reproductive stage.

IR3, IV1 and IR1 in 2015 mean irrigation three times at the reproductive stage, irrigation once at the vegetative stage and irrigation once at the reproductive stage.

Table 3
Parameterized model goodness-of-fit indicators for change in canopy cover of maize for seed production for various irrigation treatments from 2012 to 2015.

	Treatments	n	R^2	RMSE (%)	NRMSE (%)	EF	d
2012	CK	12	0.889	12.2	18.7	0.863	0.964
	SD	12	0.831	13.7	21.9	0.828	0.953
	JD	12	0.921	9.3	14.8	0.913	0.978
	HD	12	0.912	9.8	15.5	0.904	0.976
	FD	12	0.906	10.6	16.3	0.891	0.972
	MD	12	0.908	11.0	17.0	0.890	0.971
2013	W1	12	0.948	9.6	15.7	0.888	0.971
	W2	12	0.935	7.4	12.8	0.927	0.979
	W3	12	0.759	13.8	24.2	0.724	0.925
2014	W1	14	0.962	6.2	9.0	0.955	0.989
	W2	14	0.974	4.9	7.3	0.972	0.993
	W3	14	0.985	3.7	5.8	0.982	0.996
	CK	13	0.922	8.2	11.1	0.884	0.974
	IV3	14	0.924	8.8	12.8	0.898	0.977
	IV2	14	0.795	14.3	21.3	0.741	0.941
	IR2	14	0.937	8.4	12.5	0.892	0.975
2015	CK	17	0.902	9.4	12.6	0.885	0.965
	IV3	17	0.636	19.9	29.2	0.631	0.870
	IR3	17	0.960	7.2	9.5	0.906	0.973
	IV2	17	0.702	19.8	29.6	0.649	0.868
	IR2	17	0.852	14.7	20.3	0.721	0.912
	IV1	17	0.514	26.3	41.8	0.456	0.778
	IR1	14	0.880	11.9	17.9	0.829	0.940
	Overall	321	0.818	12.9	19.3	0.811	0.947

CK, SD, JD, HD, FD and MD in 2012 mean full irrigation, deficit irrigation at the seedling stage, the jointing stage, the heading stage, the filling stage, and the maturing stage respectively; W1, W2 and W3 in 2013 and 2014 mean irrigation water was supplied until the soil water content reached 65–70%, 55–60%, 45–50% of field capacity respectively; CK, IV3, IV2 and IR2 in 2014 and 2015 mean full irrigation, irrigation three times at the vegetative stage, irrigation two times at the vegetative stage, irrigation two times at the reproductive stage. IR3, IV1 and IR1 in 2015 mean irrigation three times at the reproductive stage, irrigation once at the vegetative stage and irrigation once at the reproductive stage. $R^2$is the coefficient of determination; RMSE is the root mean square error; NRMSE is the normalized root mean square error; EF is the Nash–Sutcliffe model efficiency coefficient; and d is Willmott's index of agreement.

2.6. Statistical analysis

To validate the performance of the model, we used the following five statistical indicators (Hsiao et al., 2009; Pereira et al., 2015):

$$R^2 = \left\{\frac{\sum_{i=1}^{n}(M_i - \overline{M})(S_i - \overline{S})}{[\sum_{i=1}^{n}(M_i - \overline{M})^2]^{0.5}[\sum_{i=1}^{n}(S_i - \overline{S})^2]^{0.5}}\right\}^2 \quad (11)$$

$$RMSE = \left[\frac{\sum_{i=1}^{n}(M_i - S_i)^2}{n}\right]^{0.5} \quad (12)$$

$$NRMSE = \frac{100}{\overline{M}}\left[\frac{\sum_{i=1}^{n}(M_i - S_i)^2}{n}\right]^{0.5} \quad (13)$$

$$EF = 1 - \frac{\sum_{i=1}^{n}(S_i - M_i)^2}{\sum_{i=1}^{n}(M_i - \overline{M})^2} \quad (14)$$

$$d = 1 - \frac{\sum_{i=1}^{n}(S_i - M_i)^2}{\sum_{i=1}^{n}(|S_i - \overline{M}| + |M_i - \overline{M}|)^2} \quad (15)$$

where R^2 is the coefficient of determination, RMSE is the root mean square error, NRMSE is the normalized root mean square error, EF is the Nash–Sutcliffe model efficiency coefficient, d is Willmott's index of agreement, S_i is the simulated value, M_i is the observed (measured) value, $\overline{S}$ is the mean of the simulated values, and $\overline{M}$ is the mean of the observed values. R^2 ranges from 0 to 1; higher values indicate less error variance, and normally values greater than 0.5 are considered acceptable (Santhi et al., 2001). The agreement between the simulated and observed values is good when RMSE is close to zero. The simulation is considered *excellent* when NRMSE < 10%, *good* if NRMSE is in the range 10%–20%, *acceptable* if NRMSE is in the range 20%–30%, and *poor* if NRMSE > 30% (Jamieson et al., 1991). EF can range from negative infinity to 1; EF = 1 indicates a perfect fit; EF = 0 indicates that the model predictions are as accurate as the average of the observed data; and EF < 0 indicates that the mean of the observations gives a better prediction than the model. Willmott's d ranges between 0 and 1, with 0 indicating no agreement and 1 indicating a perfect agreement between the simulation and observation.

3. Results and discussion

3.1. Parameterization of the AquaCrop model

We obtained a set of conservative model parameters from comparisons between simulated and observed values and the use of trial and error to adjust parameter values. We used observations from all experimental treatments over all years. The parameters appear to be valid for most of the irrigation treatments (Table 2). Normalized water productivity (WP^*) is one of the most important parameters in the AquaCrop model and was considered to be constant for a particular crop species (Steduto et al., 2009). Daily T was not available in this study, so daily ET was used in computing WP^*, as was done in other studies such as Hsiao et al. (2009), Farahani et al. (2009) and Araya et al. (2010b). Linear regression between biomass and the sum of the normalized ratios of actual evapotranspiration to reference evapotranspiration up to the time of each biomass measurement, over the 4 years, is presented in Fig. 2. The calculated WP^* was 20.9 g m^{-2} with R^2 = 0.902. It was lower than the default value (30 g m^{-2} to 35 g m^{-2}) given for C4 plants in the FAO AquaCrop model, and this result shows that maize for seed production differs from other crop maize.

3.2. Performance of the models

3.2.1. Canopy cover (CC)

As shown in Fig. 3, the CC values estimated by AquaCrop using calibrated parameters were closer to the observed values than the CC values obtained when using the default parameters. The AquaCrop model using default parameters overestimated CC during the development stage and underestimated it during the senescence stage. This was because the default canopy growth coefficient (CGC) and the canopy decline coefficient (CDC) were greater than the observed values in each year (Table 2), especially CDC. Paredes et al. (2014) also showed that the accuracy of the CC estimation for maize given by the parameterized AquaCrop model is greater than when using the default parameters.

The goodness-of-fit indicators relative to the estimation of CC using the calibrated parameters are given in Table 3. The results show that R^2, RMSE, NRMSE, EF, and d for all irrigation treatments were 0.818, 12.9%, 19.3%, 0.811, and 0.947 respectively. These results show that the parameterized AquaCrop model estimated CC with an acceptable accuracy for all irrigation treatments from 2012 to 2015. However, when examining the different irrigation treatments, R^2, RMSE, NRMSE, EF and d ranged from 0.514 to 0.985, 3.7% to 26.3%, 5.8% to 41.8%, 0.456–0.982, and 0.778–0.996 respectively, which suggests that errors still exist in the estimation of CC for different irrigation treatments. In 2012, estimated CC began to decrease earlier than observed CC for all treatments (Fig. 3a–f). In 2013, the model underestimated CC in the middle stage for W2 and W3, but overestimated CC for W1, which shows that the model underestimated CC in the middle stage under severe water stress for the whole growth period (Fig. 3g–i). In 2014, the model slightly underestimated CC in the development stage for all treatments (Fig. 3j–p). Moreover, the model significantly overestimated CC in the senescence stage for IV3 and IV2 (Fig. 3n–o), which shows that the model was not sensitive to water stress in the senescence stage. In 2015, the model significantly overestimated CC over the water stress

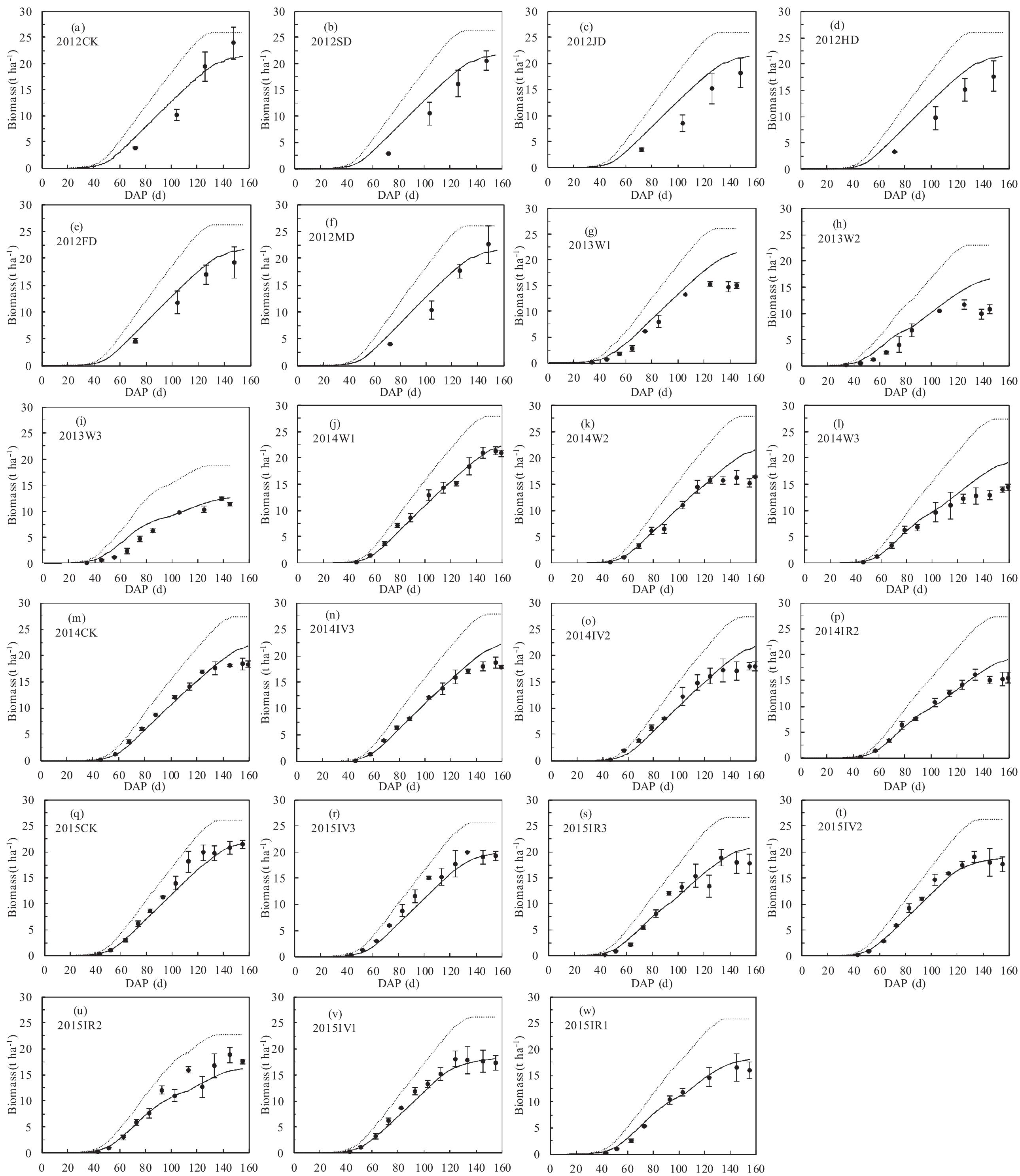

Fig. 4. Comparison of simulated biomass accumulation using default (.....) and calibrated (——) parameters with observed values (•) of maize for seed production from 2012 to 2015. DAP is days after planting.

CK, SD, JD, HD, FD and MD in 2012 mean full irrigation, deficit irrigation at the seedling stage, the jointing stage, the heading stage, the filling stage, and the maturing stage respectively.

W1, W2 and W3 in 2013 and 2014 mean irrigation water was supplied until the soil water content reached 65–70%, 55–60%, 45–50% of field capacity respectively.

CK, IV3, IV2 and IR2 in 2014 and 2015 mean full irrigation, irrigation three times at the vegetative stage, irrigation two times at the vegetative stage, irrigation two times at the reproductive stage.

IR3, IV1 and IR1 in 2015 mean irrigation three times at the reproductive stage, irrigation once at the vegetative stage and irrigation once at the reproductive stage.

period for IV3, IV2 and IV1 (Fig. 3r, t, v), which suggests that the model does not accurately simulate CC when water stress at the senescence stage led to the accelerated decrease in CC, which was similar to IV3 and IV2 in 2014. The model underestimated CC during the water stress period for IR3, IR2 and IR1 (Fig. 3s, u, w), which suggests that the model was too sensitive to water stress in the vegetative growth stage.

Katerji et al. (2013) showed that in a Mediterranean climate, an AquaCrop model accurately estimated the CC of maize with full

Table 4
Parameterized model goodness-of-fit indicators for change in biomass accumulation of maize for seed production for various irrigation treatments from 2012 to 2015.

	Treatments	n	R^2	RMSE ($t\,ha^{-1}$)	NRMSE (%)	EF	d
2012	CK	4	0.956	2.511	17.4	0.897	0.966
	SD	4	0.989	2.713	21.6	0.833	0.955
	JD	4	0.968	3.597	31.7	0.605	0.914
	HD	4	0.994	3.460	30.2	0.606	0.916
	FD	4	0.999	1.903	14.5	0.885	0.973
	MD	4	0.965	2.161	15.9	0.907	0.972
2013	W1	10	0.974	3.184	41.0	0.720	0.948
	W2	10	0.925	3.025	52.0	0.527	0.916
	W3	10	0.965	1.396	23.7	0.905	0.975
2014	W1	12	0.991	0.802	6.6	0.988	0.997
	W2	12	0.944	2.564	25.2	0.821	0.964
	W3	12	0.971	2.621	30.0	0.703	0.947
	CK	12	0.973	1.549	13.7	0.947	0.988
	IV3	12	0.981	1.770	15.9	0.927	0.985
	IV2	12	0.966	1.814	16.3	0.921	0.983
	IR2	12	0.959	1.623	16.5	0.917	0.982
2015	CK	12	0.983	1.293	10.7	0.972	0.993
	IV3	12	0.979	1.472	12.8	0.957	0.989
	IR3	12	0.950	1.635	15.6	0.938	0.985
	IV2	12	0.985	0.919	8.3	0.982	0.995
	IR2	12	0.959	1.819	17.8	0.916	0.975
	IV1	12	0.988	0.883	8.1	0.981	0.995
	IR1	9	0.988	0.951	10.9	0.976	0.994
	Overall	219	0.929	1.972	19.1	0.903	0.977

CK, SD, JD, HD, FD and MD in 2012 mean full irrigation, deficit irrigation at the seedling stage, the jointing stage, the heading stage, the filling stage, and the maturing stage respectively; W1, W2 and W3 in 2013 and 2014 mean irrigation water was supplied until the soil water content reached 65–70%, 55–60%, 45–50% of field capacity respectively; CK, IV3, IV2 and IR2 in 2014 and 2015 mean full irrigation, irrigation three times at the vegetative stage, irrigation two times at the vegetative stage, irrigation two times at the reproductive stage. IR3, IV1 and IR1 in 2015 mean irrigation threetimes at the reproductive stage, irrigation once at the vegetative stage and irrigation once at the reproductive stage. $R^2$is the coefficient of determination; RMSE is the root mean square error; NRMSE is the normalized root mean square error; EF is the Nash–Sutcliffe model efficiency coefficient; and d is Willmott's index of agreement.

irrigation, overestimated CC in the middle stage if there was moderate water stress, and that the estimated values did not match the observed values when there was severe water stress as the estimated CC decreased rapidly to zero about 60 days after planting. However, in our study the estimated CC did not decrease rapidly to zero because CC was related to the specific duration and degree of water stress. Our study also showed that for the water stress treatments over the whole growth period, the model underestimated CC during the middle stage and overestimated it during the late stage. This result is similar to the results of Andarzian et al. (2011) and Toumi et al. (2016), who studied wheat species. We found that the simulation of CC was rather sensitive to water stress during the vegetative stage, which resulted in the underestimation of CC. We also found that the model cannot simulate water stress during senescence period, which resulted in CC overestimation. These findings all together indicate that the model simulation of the response of CC to water stress during different growth stages can be improved. Paredes et al. (2014) also found that the simulation of CC for maize could be improved; it was insensitive to water stress over the whole growing season but too sensitive to water stress during the vegetative stage. Heng et al. (2009) also suggested that the simulation of CC for maize under severe water stress conditions needed to be improved.

3.2.2. Biomass accumulation

The results of simulated biomass accumulation by both the default and the parameterized AquaCrop models are given in Fig. 4. The figure shows that the estimation of biomass accumulation by the parameterized model was more accurate (i.e. closer to observed values) than that given when using default parameters. When using the default parameters the model greatly overestimated biomass accumulation during the whole growth period. This was mainly because the default WP^* (33.7 $g\,m^{-2}$) was greater than the annual observed values during 2012–2015 (24.6 $g\,m^{-2}$, 18.1 $g\,m^{-2}$, 21.7 $g\,m^{-2}$ and 26.1 $g\,m^{-2}$ respectively). The simulation showed a rapid increase in biomass accumulation that was not consistent with our observations in this study. Paredes et al. (2014) also found that an AquaCrop model with calibrated parameters simulates biomass accumulation in maize better than when the default parameters are used.

The goodness-of-fit indicators for the estimation of biomass accumulation using the calibrated parameters are given in Table 4. Results show that R^2, RMSE, NRMSE, EF, and d for all irrigation treatments were 0.929, 1.972 $t\,ha^{-1}$, 19.1%, 0.903, and 0.977 respectively, indicating that the parameterized model estimates biomass accumulation with an acceptable accuracy under different soil water stress conditions. However, for different irrigation treatments, R^2, RMSE, NRMSE, EF, and d ranged from 0.925 to 0.999, 0.802 $t\,ha^{-1}$ to 3.597 $t\,ha^{-1}$, 6.6% to 52.0%, 0.527–0.988, and 0.914–0.997 respectively, suggesting that there are still errors in the estimated values. In 2012, when compared with the control treatment CK, the parameterized model overestimated biomass accumulation for growth stages JD and HD (Fig. 4a, c, d), with RMSE values of 3.597 $t\,ha^{-1}$ and 3.460 $t\,ha^{--1}$ and NRMSE values of 31.7% and 30.2% (Table 4) respectively. These results show that the model performed poorly for deficit irrigation at the jointing and heading stages. In 2013 and 2014, the estimated and observed values of biomass were close only in the early and middle growth stages, but after that the estimated values did not match the observed values because the estimated biomass values continued to increase and the observed values tended to be constant (Fig. 4g–p). In 2015, the parameterized model estimated the final biomass for CK well, but it underestimated the biomass from 100 days to 130 days after sowing (Fig. 4q).

Andarzian et al. (2011) used AquaCrop to model wheat growth under hot and dry weather conditions in southern Iran. They showed that the model can estimate wheat biomass accumulation well for full and deficit irrigation treatments, but slightly overestimates biomass accumulation. Hsiao et al. (2009) parameterized and validated an AquaCrop model for maize and found that RMSE ranged from 0.58 $t\,ha^{-1}$ to 6.18 $t\,ha^{-1}$, and that d ranged from 0.915 to 0.999. This finding was similar to our results, where RMSE ranges from 0.802 $t\,ha^{-1}$ to 3.597 $t\,ha^{-1}$, and d ranges from 0.914 to 0.997. Our study also shows that the parameterized model can generally simulate biomass well for the early and middle stages but overestimates it at the late stage. This occurs because the calculation of biomass in an AquaCrop model (Section 2.4, Equation 3) uses the same value of WP^* during the whole growth period. We found that WP^* varied over different growth stages (Fig. 2). For example, WP^* at the late stage decreased significantly. If the model were to use different WP^* values for different growth stages, then biomass accumulation would be estimated more accurately, especially in the late stage. Hsiao et al. (2009) also found that for maize WP^* changes according to growth period. They showed a sharp increase in WP^* at the beginning of the growth period, followed by a steady gradual rate of change, and then ending with a decrease for one to several data points sampled near the end of the crop life cycle. This behavior is similar to what we found. Hsiao et al. (2009) also did not consider a change of WP^* in their AquaCrop model, and only used the stable middle portion (the time period from CC > 70% to 25% LAI senescence) to derive WP^* by fitting a linear equation. They also found errors in the estimation of biomass accumulation, especially in the mature stage, which again is similar to our results. However, Hsiao et al. (2009) thought that the biomass was underestimated because either WP^* or $Kc_{Tr,x}$ was too small. Katerji et al. (2013) studied maize in a Mediterranean climate and found that the AquaCrop model can generally estimate biomass accurately in the first half of the growth stage with full irrigation treatment, but that the model overestimates biomass significantly in the last half of the period. Again, this result is similar to our findings.

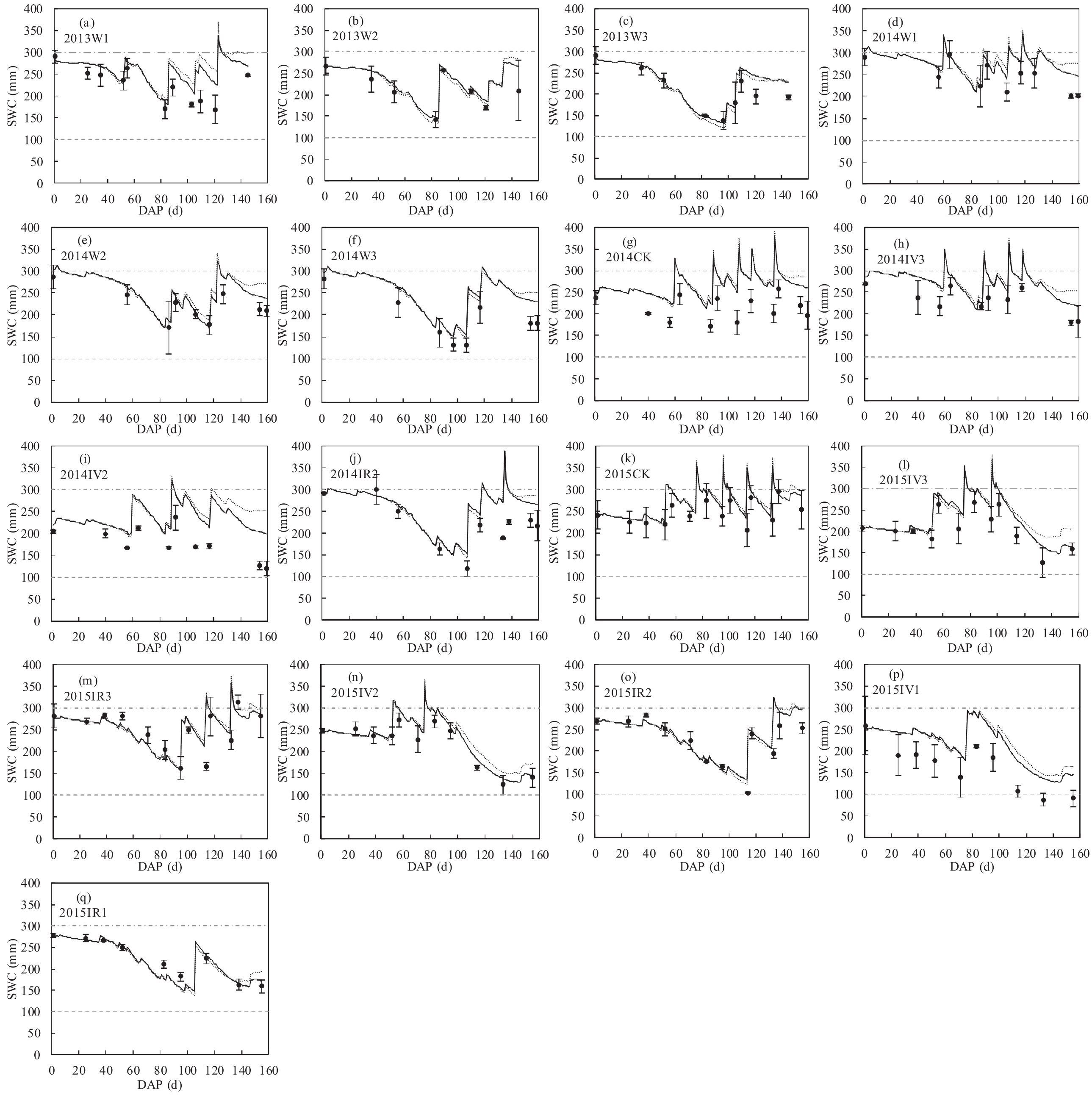

Fig. 5. Comparison of simulated soil water content (SWC, 0–100 cm) using default (……) and calibrated (——) parameters with observed values (•) of maize for seed production from 2013 to 2015. Change in soil water content was not measured in 2012. Field capacity (_ . _ . _ . _) and permanent wilting point (——) are shown.
DAP is days after planting.
W1, W2 and W3 in 2013 and 2014 mean irrigation water was supplied until the soil water content reached 65–70%, 55–60%, 45–50% of field capacity respectively.
CK, IV3, IV2 and IR2 in 2014 and 2015 mean full irrigation, irrigation three times at the vegetative stage, irrigation two times at the vegetative stage, irrigation two times at the reproductive stage.
IR3, IV1 and IR1 in 2015 mean irrigation three times at the reproductive stage, irrigation once at the vegetative stage and irrigation of one time at the reproductive stage.

3.2.3. Water content of the soil profile

Fig. 5 shows the soil water content (SWC) of the profile (0 to100 cm) estimated by the default and parameterized models for the growing seasons in the period 2013–2015. The parameterized simulations provided results that were closer to observed values than the default simulations. Paredes et al. (2014) also found differences when simulating SWC using the default parameters for maize.

The goodness-of-fit indicators for SWC are given in Table 5. The parameterized model gave good estimates of SWC under all irrigation treatments, with R^2, RMSE, NRMSE, EF, and d of 0.736, 33.1 mm, 15.2%, 0.364, and 0.854 respectively (Table 5). For different treatments, R^2, RMSE, NRMSE, EF, and d ranged from 0.594 to 0.932, 15.6 mm to 56.0 mm, 7.0% to 34.1%, −2.372 to 0.883, and 0.574–0.971 respectively. These values indicate that there is an error in the parameterized model calculation of SWC. In 2013, the model estimated SWC well for the early and middle stages but overestimated SWC for the late stage (Fig. 5a–c). In 2014, the model overestimated SWC during the whole growth period for all the treatments (Fig. 5d–j). In 2015, the parameterized model overestimated SWC in stage IR1, but gave good estimates of SWC for all other treatments (Fig. 5k–q).

Hsiao et al. (2009) found that the rate of decrease for estimated SWC is slightly less than that for observed SWC, and that SWC is overestimated by 80 mm by the end of the season. We observed a similar phenomenon in this study, such as for treatments CK and IV2 in

Table 5
Parameterized model goodness-of-fit indicators for change in soil water content (0–100 cm) of maize for seed production for various irrigation treatments from 2013 to 2015.

Year	Treatments	n	R^2	RMSE (mm)	NRMSE (%)	EF	d
2013	W1	11	0.595	37.5	16.7	0.099	0.756
	W2	8	0.841	22.5	10.6	0.668	0.921
	W3	9	0.848	22.7	10.9	0.771	0.948
2014	W1	10	0.749	25.9	10.6	0.377	0.805
	W2	9	0.915	21.5	9.8	0.608	0.924
	W3	8	0.927	32.6	17.3	0.542	0.898
	CK	12	0.725	50.1	23.5	−2.372	0.574
	IV3	10	0.721	33.9	14.8	−0.303	0.724
	IV2	10	0.594	56.0	31.6	−1.585	0.791
	IR2	10	0.703	42.7	19.3	0.325	0.824
2015	CK	14	0.808	19.7	8.0	0.416	0.869
	IV3	12	0.879	27.1	13.0	0.567	0.905
	IR3	12	0.805	21.1	8.5	0.804	0.944
	IV2	11	0.932	17.0	7.7	0.883	0.971
	IR2	12	0.878	19.6	8.8	0.856	0.962
	IV1	10	0.855	56.0	34.1	−0.115	0.758
	IR1	9	0.902	15.6	7.0	0.874	0.971
	Overall	178	0.736	33.1	15.2	0.364	0.854

W1, W2 and W3 in 2013 and 2014 mean irrigation water was supplied until the soil water content reached 65–70%, 55–60%, 45–50% of field capacity respectively; CK, IV3, IV2 and IR2 in 2014 and 2015 mean full irrigation, irrigation three times at the vegetative stage, irrigation two times at the vegetative stage, irrigation two times at the reproductive stage. IR3, IV1 and IR1 in 2015 mean irrigation three times at the reproductive stage, irrigation once at the vegetative stage and irrigation once at the reproductive stage. R^2 is the coefficient of determination; RMSE is the root mean square error; NRMSE is the normalized root mean square error; EF is the Nash–Sutcliffe model efficiency coefficient; and d is Willmott's index of agreement.

2014, and IV1 in 2015. Moreover, previous studies have shown that the AquaCrop model can simulate the variation in SWC, but that it overestimates SWC during the growth period (Farahani et al., 2009; Hussein et al., 2011; Zeleke et al., 2011; Paredes et al., 2014; Toumi et al., 2016), a finding that is similar to our results. However, Araya et al. (2010b) and Iqbal et al. (2014) found that the AquaCrop model generally estimates a lower SWC than is observed, which might be related to differences in soil textures.

3.2.4. Final biomass, harvest index, and yield

The estimated values of final biomass (B), harvest index (HI), and yield (Y) from the different irrigation treatments over the period 2012–2015 were compared with the observed values, as shown in Table 6. The difference between the observed value and the estimated value is given as a percentage of the observed value.

As shown in Table 6, among 23 treatments, the difference between the estimated and observed values of B was ≤5% for 4 treatments, ≤15% for 12 treatments, ≤30% for 19 treatments and > 30% for 4 treatments. These results show that the parameterized AquaCrop model generally estimated B well but that there are errors in the calculation. Possible reasons for the errors are: (a) one fixed value of WP^* was used for all varieties of maize for seed production, leading to systematic errors for every specific cultivar (for example, the actual WP^*, 18.1 g m^{-2}, in 2013 was smaller than the fixed value, 20.9 g m^{-2}, resulting in overestimation of B for all treatments in this year); and (b) the AquaCrop model uses a single WP^* value over the whole growth period, but we observed that the WP^* of maize for seed production varied over the different growth stages. Hsiao et al. (2009) parameterized the AquaCrop model for maize in a Mediterranean climate and found that among 13 treatments, the difference between the estimated and observed biomass is ≤5% for 5 treatments and ≤10% for 8 treatments, and that the greatest difference is 22%. These results are better than our

Table 6
Comparison of simulated and measured values of final biomass, yield and harvest index of maize for seed production using calibrated parameters for various irrigation treatments from 2012 to 2015.

Year	Treatments	Final biomass			Yield			Harvest index		
		M[a] (t ha^{-1})	S	D[b] (%)	M (t ha^{-1})	S	D (%)	M (%)	S	D (%)
2012	CK	23.928	21.399	−10.6	7.167	7.062	−1.5	30.0	33.0	10.2
	SD	20.621	21.68	5.1	7.141	7.155	0.2	34.6	33.0	−4.7
	JD	18.208	21.428	17.7	6.961	7.071	1.6	38.2	33.0	−13.7
	HD	17.680	21.483	21.5	6.424	7.084	10.3	36.3	33.0	−9.2
	FD	19.244	21.674	12.6	6.066	7.153	17.9	31.5	33.0	4.7
	MD	22.576	21.49	−4.8	7.054	7.092	0.5	31.2	33.0	5.6
2013	W1	15.041	21.384	42.2	4.871	7.056	44.9	32.4	33.0	1.9
	W2	10.780	16.563	53.6	2.848	5.438	91.0	26.4	32.8	24.3
	W3	11.357	12.565	10.6	1.876	4.0333	114.9	16.5	32.1	94.3
2014	W1	20.828	22.231	6.7	6.418	7.336	14.3	30.8	33.0	7.1
	W2	16.446	21.470	30.5	4.359	7.082	62.5	26.5	33.0	24.4
	W3	14.459	19.096	32.1	3.320	6.265	88.7	23.0	32.8	42.9
	CK	18.364	21.839	18.9	6.643	7.207	8.5	36.2	33.0	−8.8
	IV3	17.894	22.217	24.2	6.389	7.331	14.7	35.7	33.0	−7.6
	IV2	17.900	21.698	21.2	5.386	7.16	32.9	30.1	33.0	9.7
	IR2	15.471	19.06	23.2	3.855	6.253	62.2	24.9	32.8	31.7
2015	CK	21.447	21.613	0.8	7.608	7.132	−6.3	35.5	33.0	−7.0
	IV3	19.299	19.765	2.4	6.481	6.494	0.2	33.6	32.9	−2.2
	IR3	17.744	20.674	16.5	5.569	6.807	22.2	31.4	32.9	4.9
	IV2	17.653	18.819	6.6	7.096	6.032	−15.0	40.2	32.1	−20.3
	IR2	17.587	16.157	−8.1	4.993	5.213	4.4	28.4	32.3	13.6
	IV1	17.371	18.139	4.4	5.606	5.778	3.1	32.3	31.9	−1.3
	IR1	15.990	18.052	12.9	4.613	5.887	27.6	28.9	32.6	13.0

[a]M is measured; S is simulated; D is deviation. [b]D = (S − M) × 100 / M. CK, SD, JD, HD, FD and MD in 2012 mean full irrigation, deficit irrigation at the seedling stage, the jointing stage, the heading stage, the filling stage, and the maturing stage respectively; W1, W2 and W3 in 2013 and 2014 mean irrigation water was supplied until the soil water content reached 65–70%, 55–60%, 45–50% of field capacity respectively; CK, IV3, IV2 and IR2 in 2014 and 2015 mean full irrigation, irrigation three times at the vegetative stage, irrigation two times at the vegetative stage, irrigation two times at the reproductive stage. IR3, IV1 and IR1 in 2015 mean irrigation threetimes at the reproductive stage, irrigation once at the vegetative stage and irrigation once at the reproductive stage. $R^2$is the coefficient of determination; RMSE is the root mean square error; NRMSE is the normalized root mean square error; EF is the Nash–Sutcliffe model efficiency coefficient; and d is Willmott's index of agreement.

results on maize for seed production in an inland arid climate. It is worth noting that WP^* of different cultivars varied from 30.3 g m^{-2} to 33.2 g m^{-2} in Hsiao et al. (2009), but that it varies from 18.1 g m^{-2} to 26.1 g m^{-2} in our study, which accounts for the larger errors in estimates of B that we obtained.

When the estimated value of HI is compared with the observed value, the difference between the values was ≤5% for 6 treatments, ≤15% for 17 treatments, ≤30% for 20 treatments and > 30% for 3 treatments (Table 6). The reasons for the errors are: (a) the reference harvest index (HI_0) of the varieties of maize for seed production was fixed to the same value for all simulations; and (b) in the AquaCrop model HI is not sensitive to water stress: observed HI was in the range 40.2%–16.5%, with a difference of 23.7% for all irrigation treatments, while estimated HI was in the range 33.0%–31.9%, with a difference of only 1.1%. Araya et al. (2010a) validated an AquaCrop model for barley and found that the large difference between estimated and observed values of Y might have been due to using a single HI value (20%) in the model; they observed that HI for the cultivars under good conditions varies from 24% to 14% during the experimental period. A similar result was found by Nyakudya and Stroosnijder (2014), who observed that HI of maize varied from 22% to 42% whereas the AquaCrop model used a constant default value of 48%. It has also been reported that the model similarly overestimated Y for some varieties of barley and underestimated Y for other varieties because of different observed values of HI_0 among varieties (Abrha et al., 2012). Hsiao et al. (2009) suggested that HI is inaccurately estimated under water stress conditions in late stages of crop growth. Farahani et al. (2009) parameterized the AquaCrop model for cotton under full and deficit irrigation and showed that the model do not accurately simulate the effect of water stress on HI, thus causing errors in the estimation of Y.

Accurate simulation of the response of Y to water is important for agricultural production, especially in an arid region where agriculture depends heavily on irrigation. We found that for Y, among 23 treatments, the differences between the observed and estimated values were ≤5% for 7 treatments, ≤15% for 13 treatments, ≤30% for 16 treatments and > 30% for 7 treatments (Table 6). These results show that the parameterized AquaCrop model was somewhat accurate but that it contained errors. The errors in estimated values of Y resulted from the errors in estimations of B and HI under different water stress conditions. As water stress increased, the estimate of Y gradually became less accurate. Severe water stress in 2013 resulted in poor model performance. Heng et al. (2009) found that the AquaCrop model produces good estimates of Y for no water stress and mild water stress treatments, but not for severe water stress treatments, especially during the senescence period. Katerji et al. (2013) modelled maize growth using AquaCrop and found that the model gives inaccurate estimates of Y for severe water stress treatments due to inaccurate estimates of CC during the growing season. These findings are similar to those in our study, which resulted from poor estimations of WP^* and HI.

The parameterized model generally simulated crop growth process better than the final B and Y. However, AquaCrop is intended to model crop growth in its entirety, not simply the outcomes. Inaccuracies in final B and Y are due to variation in normalized water productivity (WP^*) during the different growth stages and differences in the harvest index (HI) under different water stress conditions, which are not accurately modelled. The calculation formulas in AquaCrop must be improved, since parameter adjustment that would result in accurate predictions of B and Y may distort other aspects of the model.

Although the parameterized model produces some inaccurate estimates of CC, B, Y and SWC, it has the following advantages: (a) it is simple, and needs fewer calibrated parameters than other crop models; (b) using the same parameters for different varieties of maize makes the model more widely applicable; (c) the model can accommodate diverse and complicated irrigation treatments, which increases the viability of the model with respect to water stress conditions; (d) crop phenology is the same for all applications, which maintains the simplicity of the model. On the other hand, the use of the same soil parameters for all irrigation treatments in the parameterized model can result in errors. The climate may also affect the simulation. From 2012–2015 measured precipitation ranged from 68 mm to 236 mm and ET_0 ranged from 525 mm to 667 mm. However, overall, the conservative parameters used in this study gave acceptably accurate results and we conclude that the parameterized AquaCrop model can be used to simulate full and deficit irrigated maize for seed production under plastic film mulch in an arid region of Northwest China as well as in regions with similar landscape and climate.

4. Conclusions

We calibrated the default parameters of the AquaCrop model in order use it as a parameterized model to simulate the growth of maize grown for seed production. We used a large amount of experimental data gathered in the period 2012–2015 for parameterization. Our results show that the parameterized model was more accurate than the default model. The following conclusions were drawn:

- The parameterized model did not accurately predict canopy cover when there was severe water stress. The model was sensitive to water stress during the vegetative stage, but underestimated canopy cover. The model was not sensitive to water stress during senescence and overestimated canopy cover.
- The parameterized model accurately estimated biomass in early and middle growth stages but overestimated biomass in the maturing stage, thus diminishing the overall accuracy of biomass estimation. The calculation of harvest index was not sensitive to severe water stress, which led to error in the estimate of yield.
- The model accurately simulated variations in the trend of soil water content, but in general it overestimated soil water content.

Future studies can be performed to increase the simulation accuracy for B and Y, and thus the discrepancies between the simulated and measured values could be substantially reduced. For example, simulation of the variation of WP^* in the growth period, and the differences of HI under different water stress conditions, might be improved in the AquaCrop model. Four cultivars were used in this study; the influence of the particular cultivar in the parameter estimation was not the focus of this study, but will be part of our future studies. In addition, it will be interesting to identify any correlation between water stress and crop yield in the future. The parameterized AquaCrop model can also be used to optimize the deficit irrigation schedule and to simulate the impact of future climate change on agricultural production and to model potential countermeasures.

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