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AQUACROP MODEL EVALUATION IN MAIZE UNDER DIFFERENT WATER AVAILABILITIES IN THE WESTERN OF URUGUAY

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ABSTRACT: FAO's Aquacrop (AQ) crop growth and productivity model was evaluated using four water management experiments in maize during 2009, 2010, 2011 and 2012 seasons. Model was calibrated in a hydrological crop comfort situation, based on observations of Canopy Cover (CC), Biomass (B) and Yield (Y). Firstly, proposed default parameters were used and then Canopy Growth Coefficient (CGC), Canopy Decline Coefficient (CDC) and normalized Water Productivity (WP*) were adjusted. Calibration results allowed adjusted B and Y simulations. Values for B and Y obtained from statistical indicators used were, respectively: root mean square error (RMSE) = 2085 and 841 kg ha^{-1}, Normalized Root Mean Square Error (NRMSE) = 8.7 and 6.9%, Willmott's "d" = 0.96 and 0.93 and Mean Absolute Error (MAE) = 1568 and 762 kg ha^{-1}. Results permitted to conclude that AQ simulated well both variables. Afterwards, with calibrated parameters, model was validated in crop water deficiencies and rainfed situations. Results showed greater differences between observed and simulated values. In case of water deficiencies caused around flowering, during grain filling, and accumulated in the vegetative stage plus around flowering, the model simulated both variables with errors. In rainfed crops and hydrologically different seasons, AQ estimated well B and Y when rains were abundant, and crop presented no water deficiencies. In contrast, in seasons with severe water stress in certain crop cycle stages, alternating with water comfort periods, model estimated with errors B and Y. Results suggest that in water deficiencies situations, AQ stress coefficients require adjustments in corn crops.

Keywords: Crops Simulation, Grain Production, Water Deficit, Irrigation.

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ABBREVIATIONS

AQ-Aquacrop; B- biomass; b- Regression Coefficient; CC- canopy cover; CCx- maximum root depth; CDC- canopy declined coefficient; CDI- controlled deficit irrigation; CGC- canopy growth coefficient; CP- critical period; DI-deficit irrigation; Dr- root zone humidity depletion; Es- soil evaporation; ETcact- actual crop; evapotranspiration; ETo- reference evapotranspiration; fHi- adjusted factor; HIo- reference crop harvest index; IRR- irrigation; Kc- crop coefficient; KcTrx- maximum standard transpiration coefficient; Kex- water stress coefficient; Kr- evaporation reduction coefficient; Ks- stress crop coefficient; Ksat- saturated hydraulic conductivity; LAI- leaf area index; MAE- mean absolute error; NCP- noncritical period; NRMSE- normalized root mean square error; p- fraction; AW that the crop can extract without occurring water deficit; PP- precipitation; REW- easily evaporable water; RMSE- root mean square error; SWC- soil water content; Ta- actual transpiration of the crop; TAW- total available water; Tmax- maximum temperature; Tmin- minimum temperature; WP*- normalized water productivity; Y- yield

INTRODUCTION

Summer crops have the largest sown area in Uruguay and, thereby, a high relevance in the country's exports [26]. More than 1.3 Mha are planted [17] and the main environmental limitation that explain their Y inter annual variation is water availability [24,3,12]. However, most of summer crops planted area is rainfed. Though according to [9], long term annual rain average is 1300 mm, atmospheric demands in summer are high and soils water recharges are due exclusively by precipitation (PP) which present a high variability [6]. In addition, soil water storage capacity (SWC) of Uruguay's agricultural soils is low in relation to crops potential consumption and it covers only between 20 and 30% of their requirements[12]. Because of its morphophysiological characteristics, maize is a summer crop that has high sensitivity to water deficiencies, mainly around flowering, critical period (CP), as severe water deficiencies cause significant Y decreases[4]. Grain filling is also a cycle stage in which hydric stress causes Y decreases as the grains weight is determined [11,8].

Currently, irrigation water availability does not present great limitations in the country [9] but supplementary irrigation is scarcely used for different reasons, among which high energy costs stand out [5]. This is one of the main arguments that prevent a greater adoption of irrigation, particularly in corn. Traditionally, irrigation has been used to obtain potential Y, covering the total crops water needs. However, in such energy costs situations, deficit irrigation (DI) and controlled deficit irrigation (CDI) strategies are alternatives that allow improving water use efficiency [10] and to reduce irrigation direct costs.

On the other hand, crops models that adequately simulate productivity with different water managements are tools that help to improve irrigation planning. It is possible to evaluate the cost decreases by using an alternative water management other than to satisfy crops complete demand throughout the cycle, and thereby to provide knowledge to improve the adoption of irrigation. In any case, it is essential to evaluate models locally and to study their adaptation in different situations of water availability.

FAO's AQ model [25] was proposed to simulate B production and Y in diverse crops, under different irrigation strategies, including the DI [17] and rainfed conditions [23]. Model focuses on water, it has the advantage of using a scarce number of parameters and, at the same time, it is of low sophistication which allows applicability in a wide users' spectrum [23]. This work's main objective was to evaluate AQ performance in maize in the western littoral of Uruguay, in different situations of water availability: full irrigation, CDI and rainfed crops.

MATERIALS AND METHODS

Model was parameterized in experiments carried out to study the effect of water deficiencies on corn Y, developed in an experimental irrigation field located at Paysandú (32 º22 'S and 58 º03' W), during 2009, 2010, 2011 and 2012 seasons. The experimental field soil is a Pachic Argiudoll. Tillage carried out in both experiments was conventional. Soil main hydrological characteristics are shown in Table 1.

Table 1. Experimental site soil physical and hydraulic properties.

Horizon depth (m)	Particle size (%)			Water content		
	Sand	Silt	Clay	Field capacity	Permanent wilting point	Available water
				$cm^3\ cm^{-3}$		mm
0 – 0,2	31,0	46,5	22,5	0,3	0,14	32
0,2 – 0,6	25,3	39,2	35,5	0,4	0,26	56
0,6 – 0,75	22,2	40,4	37,4	0,32	0,18	21

For each studied season, Table 2 shows monthly values of average daily maximum and minimum temperatures (Tmax.and Tmin., ℃), mean daily solar radiation ($MJm^{-2}d^{-1}$), mean reference evapotranspiration (ETo, mm), mean PP (mm), and all crop growing season parameters totals.

Trials were planted on October 27, 22, 29 and 27, respectively in 2009, 2010, 2011 and 2012, and harvested on March 2, February 28, March 13 and February 28 of 2010, 2011, 2012 and 2013, in that order. DK 692, an intermediate cycle hybrid characterized by a high Y potential in the cultivars' national evaluation was used.

Plots were 5 m long and 3.5 m wide and were composed of 5 rows at a distance of 0.7 m. Target population was 100000 plants ha^{-1} which was achieved in the four seasons. Weeds chemical control was carried out with an atrazine and metolachlor herbicides mixture, in doses of 1.5 l ha^{-1} of commercial product of each one, pre-sowing applied.

Treatments and crop stages in which AQ model calibration and validation was performed were: T1 = full irrigation, T2 = water deficiencies in CP, T3 = water deficiencies during grain filling, T4 = deficiencies in the vegetative stage plus in CP and T5 = rainfed. Treatment T4 was evaluated in 2010, 2011 and 2012 since it was not possible to install it in 2009. In crop stages of T2, T3 and T4 with no caused water deficiencies, they were under hydric comfort conditions.

Treatments T1, T2, T3 and T4 were established through two types of interventions: a) supplementary irrigation and b) interception of the PP through rain shelters in water deficiencies treatments. Irrigation was drip type, with 1.49 l h^{-1} flow 0.2 m spaced emitters tapes. It was applied according to the soil water content (SWC) variation, estimated through a simplified daily soil water balance, considering 0.7 m the maximum rooting depth.

Table 2. Monthly and all crop growing season values of daily average maximum and minimum temperatures, monthly daily mean and total growing season solar radiation, monthly average and total growing season reference evapotranspiration and precipitations.

Parameter	Season	Oct	Nov	Dec	Jan	Feb	Mar	TOTAL
Daily average								
Monthly daily average and total crop growing season maximum air temperature (℃)	2009	24	27,1	27,6	30,8	28,4	28,8	28,6
	2010	22,7	27,3	31,5	32,2	28,9	28,5	29,6
	2011	21,8	28,5	29,6	33,4	29,4	26,5	29,9
	2012	n/d	28,5	29,7	29,2	28,5	25,5	28,7
Daily average								
Monthly daily average and total crop growing season minimum air temperature (℃)	2009	10,8	16,9	17,3	19,2	19,1	17	18
	2010	10,3	13,4	17,3	20,1	18,1	16,4	16,9
	2011	16,6	15,5	15,9	18,8	19,3	16,2	17,5
	2012	nd	16,2	17,9	18,6	17,2	13,9	17,7
Daily average								
Monthly daily mean and total crop growing season solar radiation (MJ m^{-2} day^{-1})	2009	23,5	19.4	22,6	26,1	18,4	19,8	2788
	2010	21,2	26,3	26.3	24,8	22,4	20,2	3523
	2011	18	26	27	27,7	20,5	18,4	3368
	2012	nd	24,6	24,1	26,4	21,6	18,4	3008
Monthly and total crop growing season ETo (mm)	2009	170	126	133	165	106	120	482
	2010	137	172	202	177	133	144	662
	2011	103	169	186	202	129	121	683
	2012	95	152	142	165	135	108	584
Monthly and total crop growing season rainfall (mm)	2009	94	351	289	265	690	194	1549
	2010	71	39	79	137	211	55	442
	2011	205	124	48	67	368	91	698
	2012	382	42	448	52	131	137	671

SWC variations were estimated by the expression: $\Delta SWC=PP+IRR-ETc_{act}$, where: ΔSWC=SWC variation (mm), IRR=irrigation (mm) and ETc_{act}= actual crop evapotranspiration (mm), this latter calculated as $ETc_{act}=ETo \times Kc \times Ks$, being ETo (mm) the reference evapotranspiration estimated using the FAO-PM method [2], Kc=crop coefficient as those proposed by FAO, and Ks=crop stress coefficient, using for its calculation the formula proposed by FAO-PM method [2] where Ks=TAW-Dr/TAW(1-p), where Dr= root zone humidity depletion (mm), that is, the missing water in relation to soil field capacity and "p" is the fraction of the total available water (TAW) that the crop can extract without occurring water deficits. Used "p" were 0.4 TAW in the CP and 0.6 TAW in non-critical period (NCP).

SWC was measured by means of a calibrated neutron probe 503 DR HIDROPROBE (InstroTek Inc., Martinez, CA, USA).

Table 3 shows net irrigation and ETc_{act} for each treatment and season evaluated. Climatic parameters to estimate ETo were measured through an automatic weather station Vantage Pro 2^{TM} Model 6510 (Davis Instruments, Hayward, CA), located approximately 2000 m far from the experimental site. Irrigation was completed when SWC reached 90%. In treatments with water deficiencies, SWC was allowed to descend to 20% and then raised by irrigation up to 40% in NCP and up to 60% during CP.

To intercept the PP, 3.5m wide x 5m long x 2.5m maximum high steel frames with water proof canvas covers rain shelters were built. Rain shelters were placed immediately before each PP event and removed immediately after, trying not to substantially modify solar radiation and temperature conditions.

In each treatment, total B and Y were measured in 9 linear meters of the three central rows of each plot and, in addition, number m^{-2} and weight of grains were determined. In T1 in 2009 and 2011, leaf area index (LAI) was measured through a Decagon AccuPar LP 80 ceptometer and transformed into CC through the empirical equation proposed by Hsiao et al. [16] where CC = 1,005$[(1-\exp(-0.6 \times LAI)]^{1,2}$. A completely randomized blocks experimental design was used. ANOVAS and means contrasts were performed to compare the evaluated treatments, and Tukey's test at a significance level of 5% was used. Analysis were performed using the statistical package SAS v.9.2.

Table 3. Adjusted Evapotranspiration (ETc_{act}) and net irrigation, both in mm, in each treatment and season.

	Season	T1	T2	T3	T4
ETc_{act} (mm)	2009	457	371	447	443
	2010	600	432	529	294
	2011	614	468	590	272
	2012	542	434	464	364
Net irrigation (mm)	2009	158	33	112	0
	2010	401	252	330	0
	2011	385	221	356	0
	2012	354	211	230	0

AQ is a crop growth model that calculates B and Y considering actual transpiration (Ta, mm) separated from soil evaporation (Es, mm). ETc_{act}(mm day^{-1}) is calculated as the sum of Ta and Es, where: Ta = Ks x CC x Kc_{Trx} x ETo (1) and Es = Kr x (1-CC) x Ke x ETo (2) where Kc_{Trx}(non-dimensional) is the maximum standard transpiration coefficient or maximum basal crop coefficient when CC = 100%; CC (%); Ks (0-1) is the water stress coefficient; Kex is the completely wet and unshaded soil surface evaporation coefficient (non-dimensional) and Kr (0-1) is the evaporation reduction coefficient [23]. Therefore, the calculation of the two ET components is mainly linked to CC simulation.

AQ model combines four sub-models: (1) soil water balance, (2) development, growth and Y, (3) atmosphere, rainfall, evaporative atmospheric demand through ETo and concentration of CO_2, (4) crop management that includes irrigation and fertilization [23].

B (kg ha^{-1}) is estimated by the model using the crop water transpired in the growing season and WP* (g m^{-2}). WP* represents the B produced per surface unit considering the accumulated transpiration, after adjusting for the atmospheric concentration of CO_2 and ETo [23]. Y (kg ha^{-1}) is calculated as: Y = fHI HIo x B (3). HIo is the reference crop harvest index, which indicates the proportion of B in the grains and fHI is an adjustment factor that integrates five water stress factors related to leaf growth, stomatal closure, B reduction due to stress before anthesis, and failure in pollination.

CC in AQ is a fundamental parameter equivalent to the fraction of soil covered by the canopy. Model does not allow the usage of data to construct the CC curve, but it allows to calibrate the CC curve. CC calculations are made through three phases [23]: the first uses an exponential function of time,which begins at crop emergence and ends when half of the maximum CC is reached, and CC growth rate defined by the CGC parameter. The second phase uses another exponential function until the maximum CC (CCx) is reached, being the shape of the curve given by the same CGC parameter. The last phase refers to the decrease in canopy coverage after the start of crop senescence and the curve shape is defined by the CDC parameter. To parameterize the CC curves, this is, finding the CCx, CGC and CDC with best fitting to the observed values of B and Y, observed LAI data can be used to calculate CC values through a function proposed by Hsiao et al., [17].

Model input data [23] include daily meteorological data of (1) max and min T (°C), PP and ETo. Atmospheric data are referred to the annual concentration of CO_2 (2). Crop data that refer to: i) sowing dates, date on which the maximum CC is reached, date on which the maximum root depth is reached, crop senescence starting date, and date of maturity, (ii) maximum Kc_{Tr} value, (iii) minimum and maximum root depth Zr (m) and root expansion shape factor, iv) initial coverage (CCo) and CCx, CGC and CDC, (v) WP*, (vi) HIo, (vii) Ks related to canopy expansion, stomatal closure, early canopy senescence and aeration stress (3). Soil data for five maximum horizons soil. For each horizon the data requires horizon depth (m), field capacity (m^3m^{-3}), permanent wilting point (m^3m^{-3}), water content at saturation (m^3m^{-3}), and saturated hydraulic conductivity (Ksat,$m.s^{-1}$). In relation to the soil profile, the easily evaporable water (REW, mm) and the curve number (4). Irrigation data, dates and water depth applied (5). Field management practices related to salinity, soil fertility and runoff reduction.

Model calibration in corn was carried out in T1 of 2009, 2010, 2011 and 2012 seasons experiments. Calibration process was started running the model with the conservative parameters proposed by Hsiao et al. [17]. Then, based on CC observations, parameters that give the CC curve shape, i.e. CGC and CDC, were adjusted. Subsequently, the WP* was adjusted by means of a sharp trial and error process with the objective that the differences between observed and simulated B and Y values were the minimum possible.

In this study AQ was statistically evaluated with four indexes, used to measure the adjustment quality of simulation models, which are detailed below:

1)The root mean square error (RMSE) that expresses the variance of the residual errors, which values vary between 0 and +∞, and its formula is:

$$RMSE = \frac{\sqrt{(\sum (Oi - Si)^2}}{n}$$

being Oi the observed and Si the simulated values.

2) The normalized RMSE (NRMSE) defined as the relation between the RMSE and the observations mean value, expressed in percentage, which formula is:

$$NRMSE = \frac{RMSE}{\bar{O}}$$

3) Willmott's index (d)(1982), varying in a rank of -∞ and 1. The model has best adjustment when the index is close to l and it is considered a bad adjustment when "d" values are negative.

$$\mathrm{d} = 1 - \frac{\sum (Si - Oi)^2}{\sum (|\mathrm{Si} - \bar{O}| + |\mathrm{Oi} - \bar{O}|)^2}$$

4) Mean absolute error (MAE) that expresses the magnitude of the mean estimated errors.

$$\mathrm{MAE} = \frac{1}{\mathrm{n}} \sum_{1}^{\mathrm{n}} |\mathrm{Oi} - \mathrm{Si}|$$

5) Regression coefficient (b) which, if being close to 1 indicates that the simulated values are statistically close to those observed.

$$b = \frac{\sum Oi\, xSi}{\sum Oi^2}$$

RESULTS AND DISCUSSION

Aquacrop calibration

Table 4 shows the conservative and non-conservative parameters used in AQ calibration in corn, including adjustments made in CGC and CDC that shape the CC curve. Adjusted WP* value is also shown in treatments T1 of 2009, 2010, 2011 and 2012 seasons. Values of the coefficients obtained for the calibration of the CC curve were: CGC=13.8%d^{-1}, CDC=1.081%GD^{-1} and WP*=34 gr m^{-2}. Calibrated parameters presented values close to those proposed by Hsiao et al.[17] in the initial calibration of AQ in maize. In case of WP* the same value as that achieved by Abedinpour et al. [1] was adjusted. On the other hand, values obtained for CGC and CDC are higher than those indicated by Paredes et al. [21] for maize. It is possible that this adjustment response of the CGC and CDC parameters has a certain dependency on local conditions of temperatures and radiation, since they are the factors that, in absence of water and nutrients deficiencies, control crop development and growth, respectively. In the remaining conservative parameters, values proposed in the initial calibration were used [17]. Table 4 shows the set of conservative and non-conservative parameters used in model calibration.

Table 4. Conservative and non-conservative parameters used in Aquacrop model calibration for corn.

Conservative parameters	
Basal temperature	8 ºC
Maximum temperature	30 ℃
Crop coverage at 90% emergence, CCO	0.50%
Crop coverage growing coefficient, CGC	13,8% day^{-1}
Crop coverage declination coefficient, CDC	1,08% GDD^{-1}
Maximum crop coverage, CCx	90%
Crop coverage declination coefficient after reaching CCx	0,3%
Crop transpiration coefficient at 100% CC	1,10
Normalized water productivity, WP *	34 g m^{-2}
Leaf growing limit ("p" above)	0,14
Leaf growing limit ("p" below)	0,72
Stress coefficient for crop expansion	2,9
Stomatal conductance limit ("p" above)	0,69
Curve shaping stomatal stress coefficient	6
Stress coefficient for senescence ("p" above)	0,69
Curve shaping stress coefficient for senescence	2,7
Variety depending conservative parameters	
Harvesting reference index (HIo)	0,50
Non-conservative parameters	
Plants density	100000 pl ha^{-1}
GD at maximum canopy cover	700
GD at flowering	820
GD during flowering	150
GD at senescence	990
GD at maturity	1290
Maximum rooting depth (m)	0,7
Minimum effective rooting depth (m)	0,3

Figure 1 shows observed and simulated values of the CC curve in 2009 (a) and 2011 (b) seasons, with CGC and CDC parameters adjusted in the calibration process. CC curve is a key aspect in the operation of AQ, since model estimates crop transpiration through the CC and, in turn, Ta is used for total B calculation. Similarly, Abedinpour et al.[1], obtained good CC estimates under water availability conditions adjusted to corn requirements without nitrogen restrictions.

Figure 2 shows values observed and simulated by AQ of total aerial B (a) and Y (b). In both variables, a good fit was found between observed and simulated values.

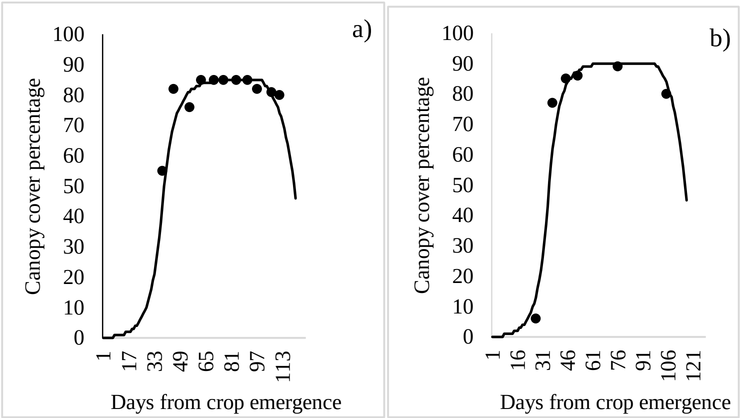

Figure 1. Values simulated by Aquacrop (line) and observed (markers) of canopy cover (CC) in full irrigation treatments (T1) of 2009 (a) and 2011 (b) seasons.

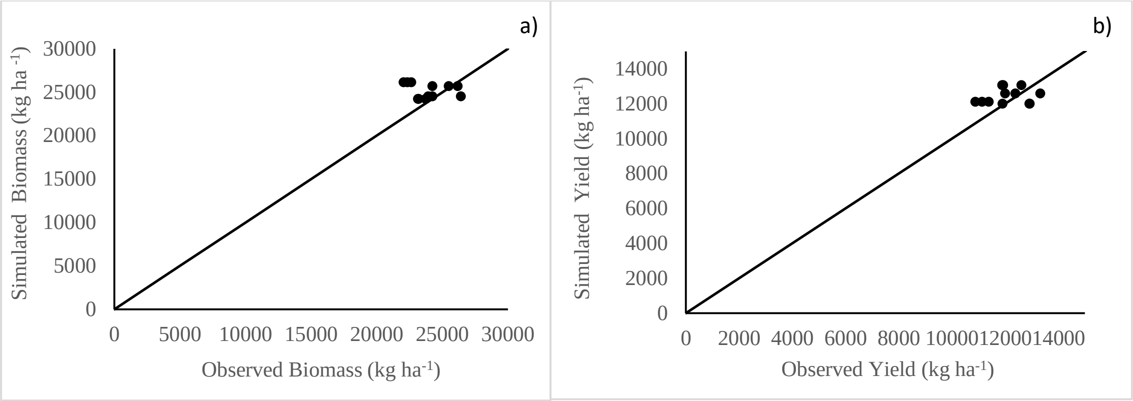

Figure 2. Relationship between values observed and simulated by Aquacrop in biomass (a) and yield (b) in full irrigation treatments experiments (T1) of 2009, 2010, 2011 and 2012 seasons.

Table 5 shows statistical indicators used to evaluate model performance in the calibration. In 2009 and 2011 seasons in which they were measured, CC was well simulated by AQ, NRMSE presented lower than 7% values being considered excellent simulations when this indicator is less than 10%, the concordance indicator "d" presented a value of 0.99 while the best result for this indicator is 1. In case of B and Y, statistical indicators used to evaluate model showed that under conditions of crop full irrigation both variables were well simulated by AQ in the four seasons.

Table 5. Root mean square error (RMSE), normalized root mean square error (NRMSE), Willmott's concordance index ("d"), mean absolute error (MAE) and regression coefficient (b) for observed and simulated biomass, yield and canopy coverage values in Aquacrop calibration.

	RMSE	MAE	NRMSE	Willmott's "d"	b
	kg ha^{-1}		%		
Biomass	2085	1568	8.7	0.99	1.04
Yield	841	762	6.9	0.96	1.03
	%		%		
CC 2009	7.2	6.6	0.09	0.9	1
CC 2011	4.5	3.1	0.1	0.99	0.97

Figure 3 shows SWC simulated by the model and observed in T1 in the four seasons. Congruence between observed and estimated values can be seen in most of the water measurements carried out.This justifies the good estimates that AQ made of total B and Y, since for the model, water availability is the key aspect for estimating both variables.
According to the results obtained, it can be concluded that adjustments made in crop parameters CGC, CDC and WP*, proposed by Hsiao et al. [17], allowed good simulations of corn B and Y in non-limiting water conditions in which the model was calibrated.

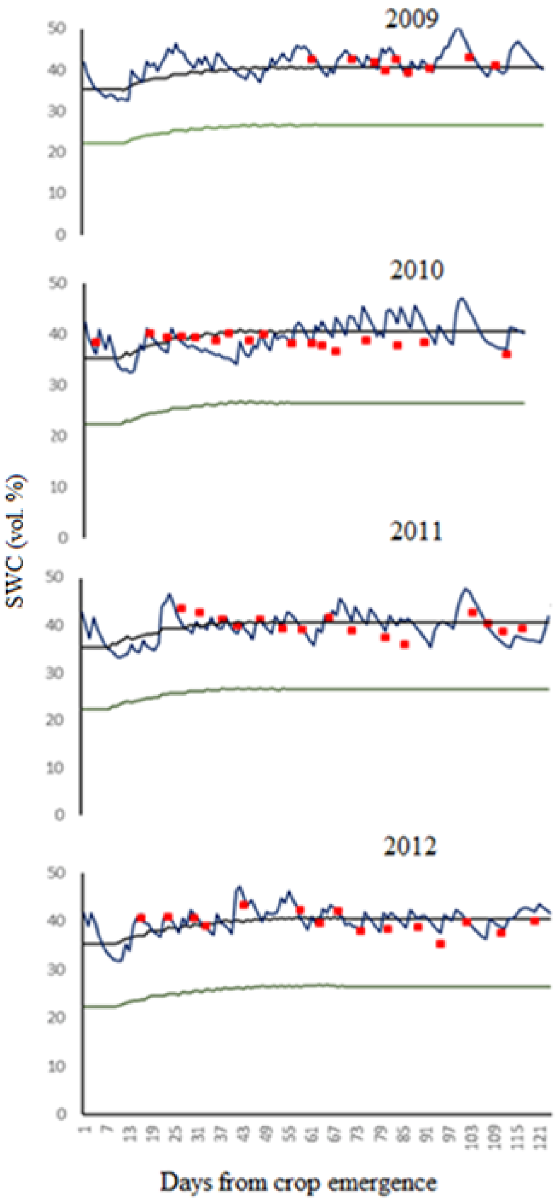

Figure 3. Full irrigation treatments in 2009, 2010, 2011 y 2012 soil water content evolution simulated by Aquacrop (blue line) and observed (red markers), soil water content at field capacity (black line) and soil water content at permanent wilting point (green line). Soil water content (vol%).

Similarly, in different regions it was found that under no water stress crop conditions, model simulated well CC, total Band Y [7]. Also, [1], added that model presented safe and adjusted simulations of B and Y in situations of full irrigation and when irrigation covered 75% of ETc.

Aquacrop validation

Model validation was made in treatments with water deficiencies caused in crop stages CP (2), grain filling (T3), vegetative stage plus in CP (T4) and rainfed crops (T5). Table 6 shows B and Y values observed and simulated by AQ and their differences in the four seasons.

Table 6. Total biomass and yield and differences (Diff.) between Aqua crop simulated (Sim.) and observed (Obs.) values, in full irrigation (T1), water deficiencies around flowering (T2), water deficiencies in grain filling (T3), water deficiencies in vegetative stage plus around flowering (T4) and rainfed crop (T5) treatments, in 2009, 2010, 2011 and 2012 seasons.

Season	Treatment	Biomass (kg ha^{-1})			Yield (kg ha^{-1})		
		Obs.	Sim.	Diff.	Obs.	Sim.	Diff.
2009	T1	23358	24219	-861	11136	12109	-973
	T2	16046	19320	-3274	5247	9131	-3584
	T3	17450	24010	-6560	7719	11995	-4276
	T5	23354	24153	-799	11186	12077	-891
2010	T1	25205	24497	708	12921	12004	917
	T2	15639	14274	1365	6437	2621	3816
	T3	20143	23625	-3482	9177	11515	2338
	T4	14502	10305	4197	5646	1615	4031
	T5	13143	8744	4399	6392	1395	4997
2011	T1	25641	25682	-41	12905	12584	321
	T2	19831	14726	5105	7722	3261	4461
	T3	21008	23068	-2060	9908	11126	-1218
	T4	17679	5189	12490	7166	157	7009
	T5	14096	7189	6907	6275	740	5535
2012	T1	24298	26136	-1838	11816	13068	-1252
	T2	19852	21198	-1346	8584	10231	-1647
	T3	18450	25553	-7103	9607	12744	-3137
	T4	17066	21115	-4049	7736	10215	-2479
	T5	15771	20553	-4782	7696	9816	-2120

In the majority of treatments with caused water deficiencies (T2, T3 and T4) it was found that AQ model simulated maize B and Y with errors. In treatment with water deficiencies in grain filling (T3), model over estimated B and Y in the four seasons. Hydric deficiencies during grain filling cause early crop senescence losses of B, diminution of the canopy coverage and, as a consequence of this, diminution of Y due to lower grains weight. [7,16] agree that AQ model does not simulate well severe water deficiencies in corn final stages. Hydric deficiencies in grain filling cause losses of B and Y that vary between 20 and 30% of the crop potential [11,8]. In the AQ simulations carried out, B and Y losses during grain filling due to severe water deficiencies varied between 1 and 12%. Simulations results show clearly that AQ does not have certainty to model water deficiencies effects in grain filling, and therefore does not simulate well the B and Y decreases that occur in that stage.

In case of water deficiencies caused in CP (T2), in two of the seasons AQ over estimated B and Y, and in the other two seasons it underestimated both variables. Additionally, it was verified that in seasons with relatively scarce PP, model underestimated them. In contrast, in 2009 season with abundant PP throughout the cycle, and in 2012 with abundant PP greater than 400 mm in crop initial stages alternating with deficiencies in other stages, AQ overestimated both variables. In reviewed literature there is no record of model performance evaluation in situations with severe water deficiencies solely around flowering. This is a maize key development stage and water deficiencies cause significant Y decreases [11,8,4] due to corn strong apical dominance that induces spikes to be relegated to the male panicle in crop water stress situations [4]. Water stress in CP affects viable grains number negatively, with Y decrease consequences [13,27,15].Water deficiencies located in this stage can lead to losses between 40 and 50% of the potential Y [11,8]. In no evaluated case with deficiencies around corn CP AQ simulations were correct.

In 2010, 2011 and 2012 seasons, effects of accumulated water deficiencies in the vegetative stage plus in CP (T4) were evaluated. In this case, AQ simulations of B and Y presented the biggest errors. As seen in Table 6, water deficiencies in T4 were the longest among those evaluated, model showed strong underestimations in 2010 and 2011, both in B and Y. In contrast, in 2012 errors in the simulation were in the opposite direction, that is, AQ simulated higher values of B and Y to those observed. As already mentioned, in 2010 and 2011 the PP were scarce while relatively abundant in 2012 and the trend in the simulations was the same as that found in T2, that is to say, in seasons with scarce PP simulations underestimated B and Y, and in years with elevated PP, AQ showed over estimates in both variables.

Results obtained in rainfed crops show different levels of adjustment according to the evaluated season. In season 2009, characterized by PP exceeding 1500 mm during the crop cycle, allowing a high water availability throughout it, the model showed a good fit between B and Y simulated and observed values, as happened with crop full irrigation treatments, confirming that when water requirements in maize are covered, either by irrigation or by PP, model simulates well B and Y.

In contrast, in 2010 and 2011 seasons, scarce PP during December (79 and 48 mm, respectively), and January (43 mm, until 25th. In 2010 and 67 mm in 2011), caused significant water deficiencies in CP of rainfed crops. In this situation, AQ underestimated B and Y with respect to the observed values, as occurred with treatments with deficiencies caused in CP, and with deficiencies accumulated in the vegetative stage plus in CP, in both seasons. This AQ behaviour to simulate well under good water availability and to present errors in severe water stress situations was verified and discussed by [15,7,19]. In 2012 season, when rainfed crop experienced better water conditions than in 2010 and 2011, alternating good water availability and scarcity stages, the model overestimated total B and Y.

Table 7 shows the statistical indicators of fitting goodness used to evaluate AQ simulations of B and Y for treatments with caused crop water deficiencies and rainfed. It was found that RMSE and NRMSE presented high values. RMSE in all cases was far above 0, which is the perfect adjustment value, and NRMSE exceeded 20%, considered the upper limit for adjusted simulations. MAE values were high in all cases and Willmott’s "d" match index showed values far from the unit, and the regression coefficient b indicated overestimates for the T3 and underestimates for the T2, T4 and T5 treatments, in both variables.

Table 7. Root mean square error (RMSE), normalized root mean square error (NRMSE), mean absolute error (MAE), Willmott’s concordance index ("d") and linear regression coefficient (b) for water deficiencies around flowering (T2), in grain filling (T3), in vegetative plus around flowering (T4) and in rainfed crops (T5) treatments, in seasons 2009, 2010, 2011 and 2012.

	RMSE (kg ha^{-1})	MRMSE (%)	MAE (kg ha^{-1})	“d”	b
Yield					
T2	3698	52	3452	0.4	0.87
T3	3397	37	3115	0.39	1.3
T4	5026	73	4506	0.41	0.61
T5	3966	50	3415	0.69	0.84
Biomass					
T2	3828	21	3349	0.43	0.94
T3	5948	31	5474	0.39	1.27
T4	5026	73	4506	0.41	0.61
T5	5000	30	4301	0.81	0.94

Figure 4 shows root zone SWC simulations evolution carried out by AQ, in treatments and seasons evaluated. Water evolution presented the expected trends, both in treatments with crops full irrigation with high water contents throughout the cycle, and in those with water deficiencies caused in different stages. In rainfed crops the behaviour was different in each season due to PP irregularity.

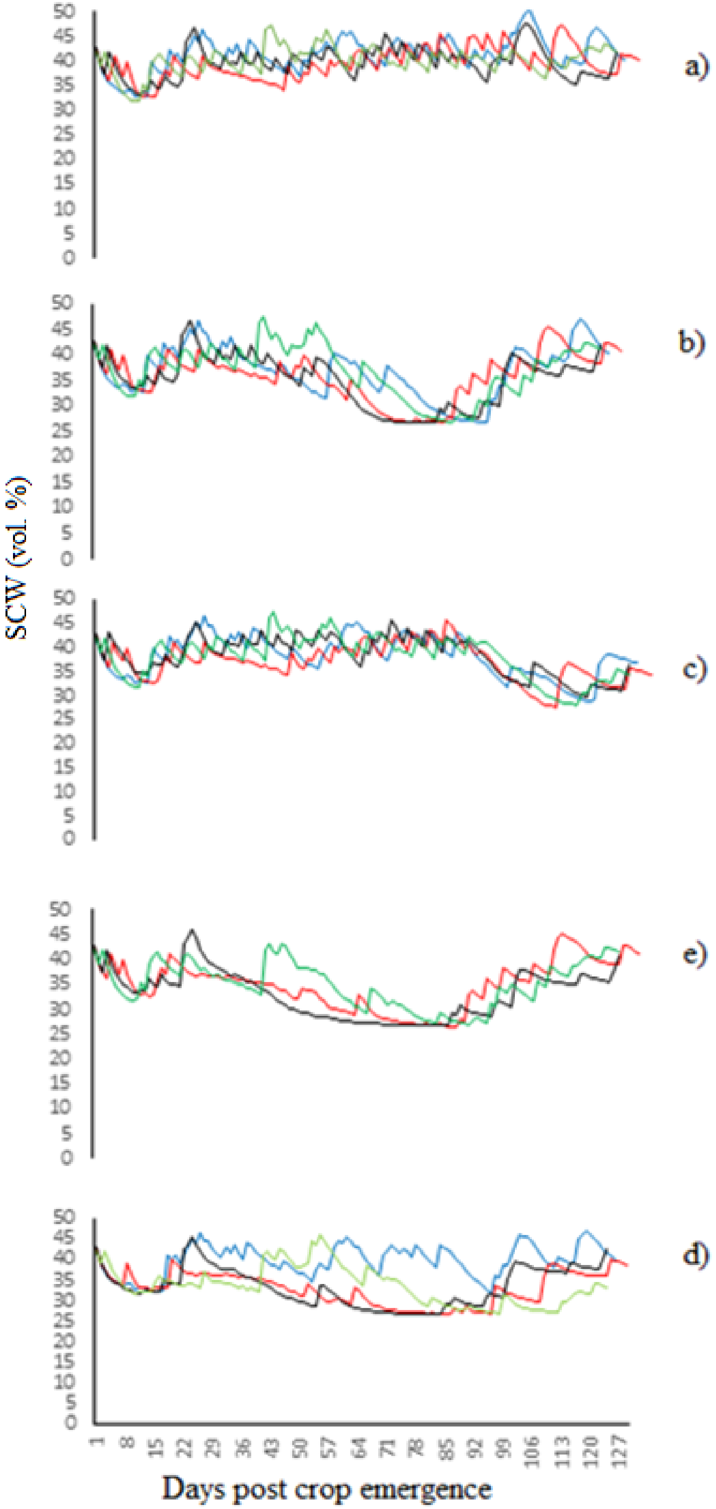

Figure 4. AQ model simulations evolution of corn cycle root zone soil water content (SWC, vol%) in treatments: a) full irrigation (T1), b) deficiencies in CP (T2), c) deficiencies in grain filling (T3), d) deficiencies in vegetative stage plus in PC (T4), and e) rainfed (T5). Respective seasons and colour lines: 2009 light blue, 2010 red, 2011 black, and 2012 green.

Figure 5 presents SWC evolution of AQ simulations and measurements in 2011 season, in evaluated treatments. It is clear the good fit between SWC in AQ simulations and in observed values in crop full irrigation situation. On the other hand, discrepancies between soil water simulations and measurements were verified in different stages of the crop cycle, both in treatments with caused water deficiencies (T2, T3 and T4) and T5. In T2 and T4, model simulated a SWC below the measurements in most of the stages, even with low water levels close to permanent wilting point. In turn, as indicated, in both treatments of 2011 season model strongly underestimated B and Y (Table 6).

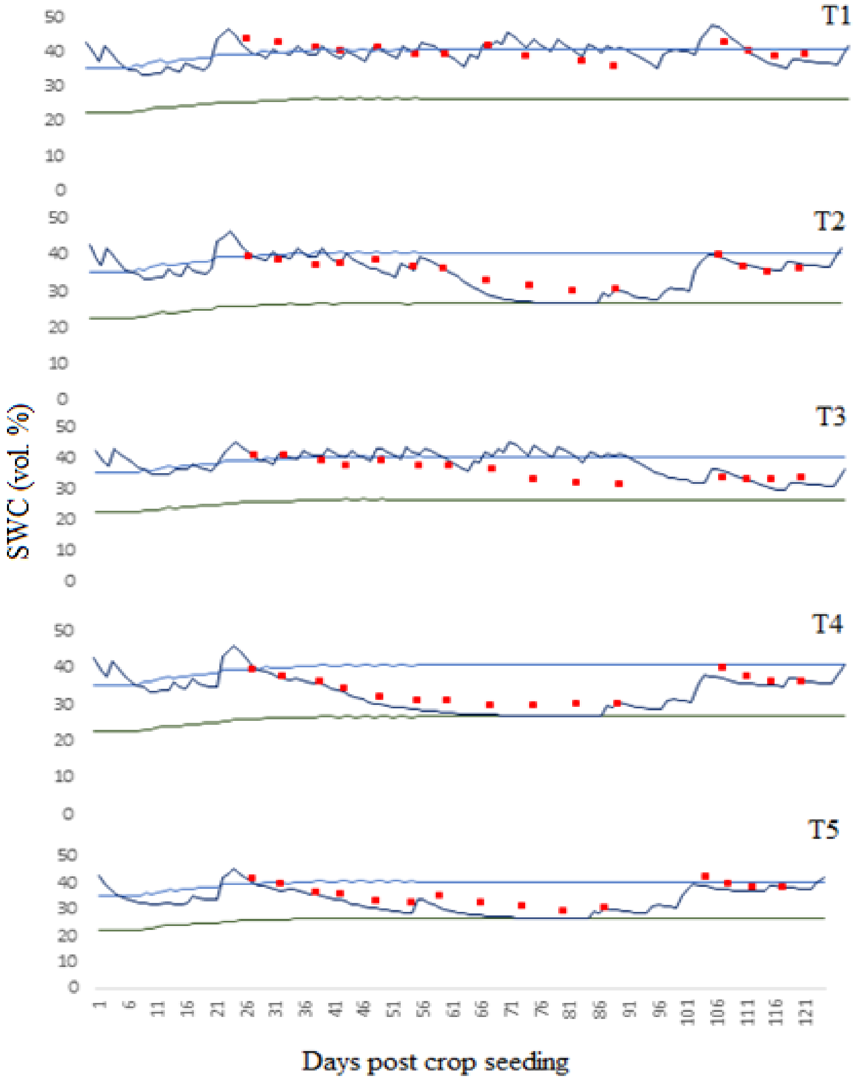

Figure 5. Root zone soil water content (SWC, vol%) evolution simulated by Aquacrop (blue line), measurements made with neutron probe (red markers), content at field capacity (light blue line) and content at permanent wilting point (green line), in 2011 season, in treatments with full irrigation (T1), water deficiencies around flowering (T2), water deficiencies in grain filling (T3), water deficiencies in the vegetative stage plus around flowering (T4) and rainfed crop (T5).

Similarly, [1] and [7] founded that in situations of severe water deficiencies during crop cycles in which only 50% of the ETc was covered, simulations of B and Y developed by AQ in maize were not adjusted to the observed data. Figure 5 shows root zone SWC simulations in T3 are mostly above the measurements and model overestimated B and Y. Again, in T5, model simulated SWC values lower than measurements and, in turn, underestimated B and Y, as indicated above.

Figure 6 shows the relationship between simulated and observed values of total B and Y for all the treatments with caused water deficiencies and rainfed crop.

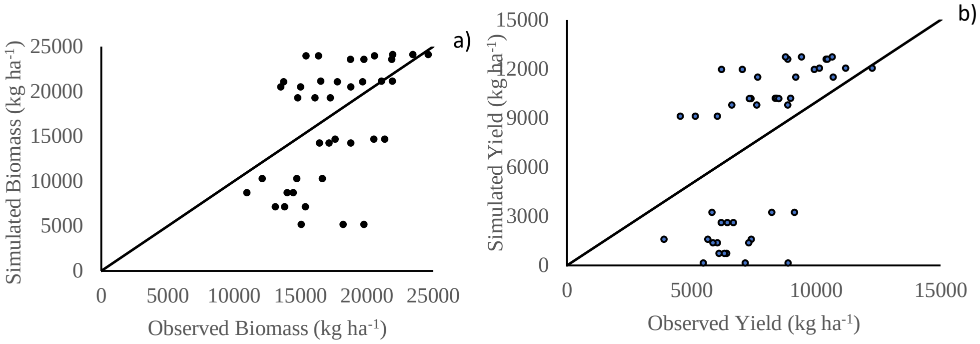

Figure 6: Relationship between observed and AQ simulated values of total biomass (a) and yield (b) for the set of treatments: water deficiencies around flowering (T2), water deficiencies in grain filling (T3), water deficiencies in vegetative stage plus around flowering (T4) and rainfed crop (T5).

Observed and simulated values dispersion demonstrates AQ problems to model both variables in situations of corn crop water deficiencies. According to the information presented in figure 5, it is possible that errors are due to problems in root zone water content simulation when there are severe deficiencies. Based on the results obtained, we interpret that model does not simulate adequately the effects of water deficiencies in corn. It is possible that AQ does not present good adjustments of Ks for severe water deficiencies. On the other hand, from results obtained in rainfed crops, it can be inferred that model operation depended on PP characteristics in each season. In seasons in which PP were abundant and allowed good water availability for most of the crop cycle, AQ performed adjusted simulations of B and Y. On the contrary, when PP were scarce and there were severe water deficiencies, simulations showed errors in relation to values observed in both variables.

CONCLUSIONS

AQ model was evaluated during four years in corn experiments with different water availabilities. After adjustments made in the calibration process in CGC, CDC and WP* parameters, model showed good predictions of B and Y in situations of crops full irrigation.

On the opposite, in conditions of water deficiencies in CP, AQ simulated with errors. In seasons with scarce PP it underestimated B and Y, as in high water availability seasons it overestimated results in both variables. In situations with deficiencies in grain filling, model overestimated B and Y through the four seasons. In treatments with water deficiencies accumulated in vegetative stage plus in CP and in seasons with low PP, model strongly underestimated both variables while overestimated them in high PP seasons.

Results in rainfed crops confirmed AQ good functioning when water availability is not restrictive, in this case due to abundant PP. However, in seasons with water deficiencies, model underestimated the observed values of B and Y. Results obtained lead to infer that AQ does not present adjusted stress coefficients values and that this produces problems in soil water modelling that later are translated into B and Y simulations with errors in severe water deficiencies situations.

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Conflicts of Interest

The author declares no conflict of interest.

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