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Performance of the AquaCrop model for corn hybrids under different irrigation strategies[1]

Desempenho do modelo Aquacrop para híbridos de milho sob diferentes estratégias de irrigação

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HIGHLIGHTS:

The AquaCrop model is efficient in estimating corn crop yield.
Crop data used in the model calibration fits different corn hybrids, demonstrating the robustness of the model.
Decisions based on irrigation strategies can be made by using the AquaCrop model.

ABSTRACT: The objective of this study was to evaluate the performance of the AquaCrop model in the estimation of grain yield and crop water yield for nine hybrids of corn with different irrigation strategies in the municipalities of Santiago, Chile, and Alegrete, in the western region of the state of Rio Grande do Sul, Brazil. Data on climate, soil, management and crop yield over four crop seasons (2015 to 2019) were used, the first two in Santiago city, and the third and fourth in Alegrete city. The experimental design was randomised blocks, consisting of five irrigation treatments (0, 50, 75, 100 and 125% of crop evapotranspiration), and four, six and one hybrid, respectively, for the first, second and third growing season. In the fourth crop season, one hybrid was considered and the treatments consisted of suppression in water supply to the crop during its reproductive period, corresponding to ETc during vegetative ($ETc_{Veg.}$) and reproductive ($ETc_{Rep.}$) phases, as follows: 0, $50_{Veg.}/25_{Rep.}$, $75_{Veg.}/37.5_{Rep.}$, $100_{Veg.}/50_{Rep.}$ and 100% of ETc. The performance of the model, evaluated through statistical indicators, was "excellent" and "good" for the simulation of grain yield and crop water productivity, respectively. There was a tendency of the model to overestimate the results under conditions of water deficit, this being more pronounced under severe deficit than under mild deficit, or in the reproductive period of the crop, and a tendency to underestimate the results under conditions of irrigation without deficit, i.e., 100 or 125% ETc.

Key words: *Zea mays* L., modelling, water management, water deficit, corn hybrids

RESUMO: O objetivo deste trabalho foi avaliar o desempenho do modelo AquaCrop na estimativa da produtividade de grãos e de água da cultura para nove híbridos de milho com diferentes estratégias de irrigação nos municípios de Santiago, Chile, e Alegrete, na região oeste do Estado do Rio Grande do Sul, Brasil. Foram usados dados de clima, solo, manejo e cultura de quatro estações de cultivo (2015 a 2019), sendo as duas primeiras em Santiago, e as duas últimas em Alegrete. O delineamento experimental foi em blocos casualizados, composto por cinco tratamentos de irrigação (0, 50, 75, 100 e 125% da evapotranspiração da cultura), e quatro, seis e um híbrido, respectivamente, para a primeira, segunda e terceira estação de cultivo. Na estação de cultivo 2018/19, os tratamentos apresentaram níveis de supressão no fornecimento de água à cultura no seu período reprodutivo, correspondendo a ETc durante a fase vegetativa ($ETc_{Veg.}$) e reprodutiva ($ETc_{Rep.}$), como segue: 0, $50_{Veg.}/25_{Rep.}$, $75^{Veg.}/37{,}5_{Rep.}$, $100_{Veg.}/50_{Rep.}$ and 100% of ETc. O desempenho do modelo, avaliado por meio de indicadores estatísticos, foi "excelente" e "bom" para simulação da produção de grãos e produtividade de água da cultura, respectivamente. Houve tendência de o modelo superestimar os resultados em regime de déficit hídrico, sendo mais expressivo em déficits severos do que em déficits leves, ou no período reprodutivo da cultura, e, tendendo a subestimar os resultados em condições de irrigação sem déficit, com 100 ou 125% de ETc.

Palavras-chave: *Zea mays* L., modelagem, manejo de água, déficit hídrico, híbridos de milho

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Introduction

Cultural and climatic factors are the ones that most affect corn production. Therefore, knowledge on hybrids in a given environment is fundamental in decision making and, when it comes to irrigation, the choice is made by those with highest yields, associated with improved crop water productivity without compromising the production and profit (Pizolato Neto et al., 2016).

For climate factors, the rise in temperature, the change in intensity patterns and precipitation frequency, which result in warmer and drier weather conditions and generate water deficit, are the most significant (Twumasi et al., 2017).

One of the greatest challenges in today's agriculture is to establish optimal irrigation strategies to improve crop water productivity without compromising production and profit; that can be achieved through modelling.

Thus, the AquaCrop model, developed by the Food and Agriculture Organization (FAO), based on the simplified study of the processes and flows of the soil-water-plant-atmosphere system by Doorenbos & Kassam (1979), is a tool that can be used efficiently to predict the impacts of water deficit on the productivity of crops such as corn.

For corn, recent studies have evaluated the effects of water stress levels, irrigation, nitrogen and sowing density in the estimation of grain yield; biomass; water use efficiency and different hybrids; the impact of crop production on climate change; and simulation of evapotranspiration (Zhao et al., 2019).

Considering the growth of irrigated corn production in the West Frontier Region of the state of Rio Grande do Sul, Brazil, where rainfall is poorly distributed during the growing season, the objective of this study was to evaluate the performance of the AquaCrop model in the simulation of grain yield and crop water yield for nine maize hybrids subjected to different irrigation strategies.

Material and Methods

The study was developed in the municipalities of Santiago, Chile (29º 09' 50" S, 54º 32' 32" W, altitude 439 m), and Alegrete , in the western region of the state of Rio Grande do Sul, Brazil (29º 71' 16" S, 55º 52' 61" W, altitude 121 m), with humid subtropical climate (Cfa), considering the crop seasons from 2015 to 2019 in soils classified as Oxisol (0.17 ha), and Ultisol (0.11 ha).

Data from four crop seasons were used: two in Santiago (2015/16 and 2016/17) and two in Alegrete (2017/18 and 2018/19). The experiments were in randomised blocks with four replicates for Santiago and three replicates for Alegrete. The treatments corresponded to 0, 50, 75, 100 and 125% of crop evapotranspiration (ETc) in the first three crop seasons.

In the 2018/19 crop season, the treatments corresponded to 50% water suppression to the crop during its reproductive period in order to verify the behaviour of the water deficit in this phase and the performance of the model in estimating productivity in this situation. Thus, the last season treatments consisted in suppression levels in providing water to the crop on its reproductive period, corresponding to ETc during vegetative ($ETc_{Veg.}$) and reproductive ($ETc_{Rep.}$) phases, as follows: 0, $50_{Veg.}/25_{Rep.}$, $75_{Veg.}/37.5_{Rep.}$, $100_{Veg.}/50_{Rep.}$ and 100% of ETc.

The corn hybrids used were AG 9025, AG 9045, DKB 240 and Status VIP3 (2015/16 crop season), AG 9025, AG 8780, DKB 177, DKB 230, DKB 290 and P1630H (2016/17 crop season), and AG 8780 (2017/18 and 2018/19 crop seasons). Sowing and harvesting dates were October 5, 2015 and February 24, 2016 (2015/16 season), October 30, 2016 and March 20, 2017 (2016/17 season), November 6, 2017 and March 21, 2018 (2017/18 season), and November 6, 2018 and April 2, 2019 (2018/19 season). The hybrids used are of early and super-early cycle, which, according to Cruz et al. (2015), correspond to thermal requirements of 831-890 and 780-830 degree-days, respectively.

For irrigation, a conventional sprinkler system with a spacing of 12 × 12 m was used, consisting of a main line measuring 48 m and five fixed lateral lines each measuring 24 m. The sprinklers were connected to the lateral lines at a spacing of 12 m and a height of 2 m from the ground. The irrigation management was based on crop evapotranspiration, according to Eq. 1:

$$ETc = ETo\ Kc \quad (1)$$

where:

ETc - crop evapotranspiration, mm per day;

ETo - reference evapotranspiration, mm per day; and,

Kc - crop coefficients (0.4, vegetative development; 1.2, flowering to grain filling; 0.6, grain filling at maturity; Doorenbos & Kassam, 1994).

For the climate, daily data on air temperature (ºC; Figure 1B), accumulated rainfall, irrigation and reference evapotranspiration (Figure 1A) obtained from meteorological stations installed near the study fields were used.

For Santiago city, the meteorological station presented geographic coordinates of 29º 19' 15" S and 54º 88' 56" W, and altitude of 390.03 m, code A833, and for Alegrete city 29º 71' 16" S, 55º 52' 61" W, and altitude of 120.88 m, code A826.

The ETo (mm per day; Figure 1A) was evaluated by the method of Penman-Monteith (Allen et al., 1998) from the variables collected from the meteorological stations. The mean annual atmospheric CO_2 concentration (ppm), considered as that measured by the Maula Loa, Hawaii, observatory (410.55 ppm - 2020), available in the default file of the AquaCrop model.

The air temperature averaged 22.5-24.2 ºC, showing low variation for the places and years studied, and the averages obtained in the months of December and January (23.9 and 23.6 ºC, respectively, for Santiago city and 25.3 and 25.0 ºC, respectively, for Alegrete city) were below those considered ideal for the municipality of Santiago. However, these are the months with the most favourable thermal conditions for corn, as they are between 25 and 30 ºC (Bergamaschi et al., 2004).

Rainfall during the seasons 2015/16 and 2016/17 was higher for Santiago (1436.1 and 1189.2 mm, respectively) than for Alegrete (500.0 and 922.2 mm, respectively). On the other hand, the ETo averages for the seasons 2017/18 and 2018/19 were lower for Santiago (4.7 and 4.0 mm per day, respectively) than for Alegrete (5.8 and 5.2 mm per day, respectively), which corroborates the increase in air temperature.

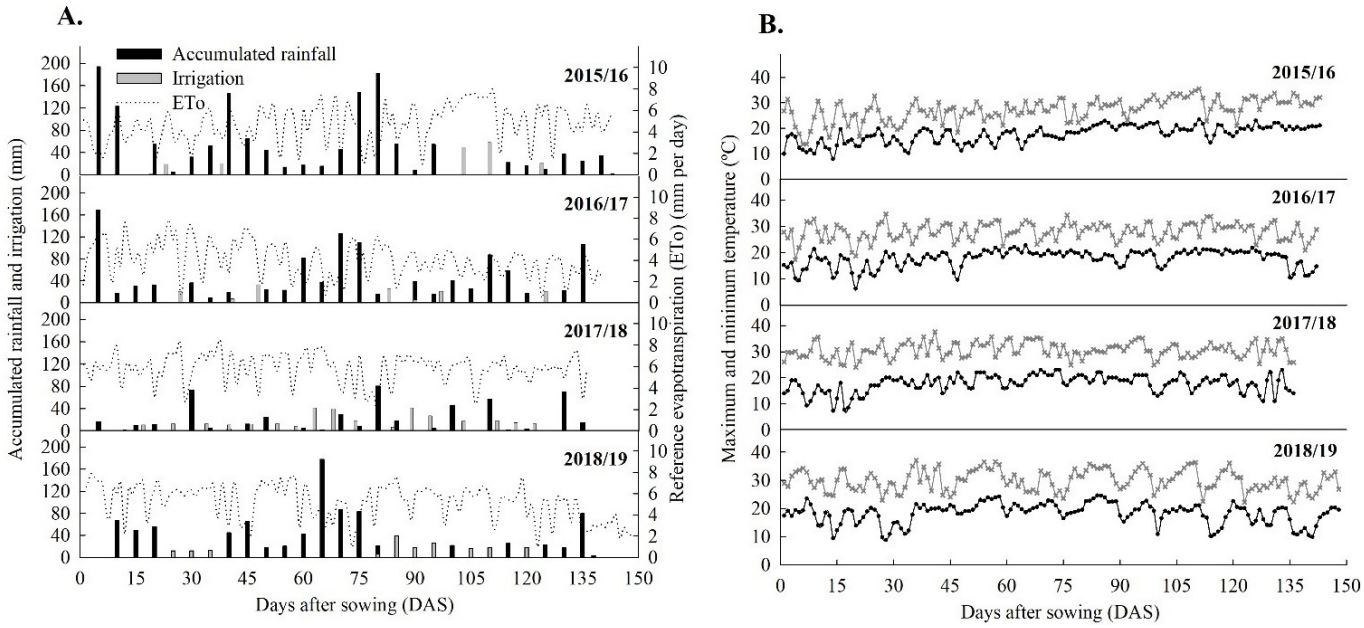


Figure 1. Accumulated rainfall, irrigation and reference evapotranspiration (A), and maximum and minimum air temperature (B) for the study seasons: Santiago, Chile (2015/16 and 2016/17) and Alegrete, RS, Brazil (2017/18 and 2018/19)

According to the Climate Atlas of Rio Grande do Sul state, the average rainfall for Santiago and Alegrete corresponded to 1934.2 and 1597.8 mm, respectively, and for the months of corn cultivation (October to March) these averages are around 971.8 and 847.5 mm, respectively.

Regarding soil characteristics, according to Table 1, the soil profile was analysed at a depth of 0.5 m, this corresponding to the maximum concentration of the effective corn roots, which, according to Albuquerque & Resende (2009), is from 0.4 to 0.6 m.

For the crop, the model divides the characteristics into conservatives, which do not change with geographical location and management practices, are applicable to different conditions and are not specific to each cultivar, and non-conservatives, which are affected by climate, management, soil conditions, and are specific for each cultivar (Raes et al., 2009; Steduto et al., 2009).

For the Tbmin and Tbmax basal temperatures, ETo and CO_2 normalised crop water yield (WP*), and (WP), the values for corn proposed by Hsiao et al. (2009) were used. Canopy ground cover (CSD) and plant density (Dp) were determined in the study crop seasons. From Steduto et al. (2009), the water yield of the ETo and CO_2 normalised crop can be considered constant for a given crop with no limitation on mineral nutrients and independent of water stress conditions, except for extremely severe ones.

The distinction of the stages of crop that comprised the sowing times to emergence (TSE), flowering sowing (TSF), senescence seeding (TSS), sowing at maturity (TSM), sowing at maximum root depth (TPMR), and flowering length (TCF), were observed in the beginning of its occurrence and its duration. The minimum (PR_{min}) and maximum (PR_{max}) effective depth of the root and its expansion form factor ($F_{exp.\ root}$) were considered according to Hsiao et al. (2009) for corn crop.

The maximum canopy cover (CCmax), consistent with the beginning of flowering, was estimated by converting the leaf area index (LAI) ($m^2\ m^{-2}$), experimentally measured according to Heng et al. (2009), while the coefficients of growth (CCD) and canopy decline (CDD) were adjusted in the model. The sensitivity of the crop to soil moisture, which relates the lower limit of canopy expansion ($LI_{exp\ canopy}$) to the upper limit of canopy expansion ($LS_{exp\ canopy}$), stomatal control ($LS_{est.}$), canopy senescence ($LS_{sen.}$), and their respective water stress form factors: $F_{exp\ canopy}$, F_{est} and F_{sen}, were adjusted for each irrigation treatment.

The simulated grain yield and biomass and the crop water productivity in relation to final grain production were estimated by Eqs. 2, 3, 4 and 5:

$$B = 0.01WP^{*} \cdot \sum Tr \quad (2)$$

$$Tr = Ks_{sto}\ Kc_{Tr}\ ETo \quad (3)$$

$$Y = B\ HI \quad (4)$$

$$WP = 100\frac{Yo}{\sum ET} \quad (5)$$

where:

B - biomass production, t ha^{-1};
WP* - ETo and CO_2 normalised crop water yield, kg m^{-3};
Tr - crop sweating, mm;
Ks_{sto} - water stress coefficient for stomatal closure;
Kc_{Tr} - maximum crop transpiration coefficient;
ETo - reference evapotranspiration, mm;
Y - simulated grain yield, t ha^{-1};
HI - adjusted season index;
WP - water yield during grain formation, kg m^{-3};
ET - simulated crop evapotranspiration, mm; and,
Yo - observed grain yield, t ha^{-1}.

The observed production, biomass, reference season index and crop water productivity were estimated according to Eqs. 6, 7, 8 and 9:

Table 1. Soil and crop characteristics used in the calibration and validation of the AquaCrop model

Soil characteristics						
Place	Depth (m)	Textural class	Soil moisture ($m^3 m^{-3}$)			K_{sat} (mm day^{-1})
			θ_{PMP}	θ_{CC}	θ_S	
Santiago	0.00-0.10	Sandy clay franc	0.16	0.29	0.43	250.10
	0.10-0.30		0.17	0.30	0.47	191.15
	0.30-0.50		0.17	0.30	0.55	170.75
Alegrete	0.00-0.10	Sandy franc	0.08	0.23	0.35	442.08
	0.10-0.30		0.11	0.25	0.37	476.16
	0.30-0.50		0.12	0.26	0.42	469.44

Crop characteristics			
Conservative	Units	Santiago (AG 9025)	Alegrete (AG 8780)
Tb_{min}	ºC	10	10
Tb_{max}	ºC	30	30
CSD	cm^2	6.5	6.5
Dp	pl ha^{-1}	85,000	80,000
WP*	g m^{-2}	33.7	33.7
WP	g m^{-2}	100	100

Non-conservative	Units	Treatments (%ETc)									
		0	50	75	100	125	0	50	75	100	125
TSM	days	11.0	11.0	11.0	11.0	11.0	10.0	10.0	10.0	10.0	10.0
CC_{max}	%	80.0	84.0	84.0	84.0	85.0	89.0	89.0	93.0	95.0	94.0
CCD	% per day	11.4	11.3	11.3	11.3	11.3	14.2	14.2	14.3	14.3	14.3
CDD	% per day	10.7	10.8	9.70	8.00	9.90	10.7	12.0	12.7	12.7	13.0
TSS	days	119	119	119	119	119	105	105	105	105	105
TSF	days	78.0	78.0	78.0	78.0	78.0	64.0	64.0	64.0	64.0	64.0
TCF	days	9.00	9.00	9.00	9.00	9.00	11.0	11.0	11.0	11.0	11.0
TSM	days	143	143	143	143	143	136	136	136	136	136
PR_{min}	m	0.30	0.30	0.30	0.30	0.30	0.30	0.30	0.30	0.30	0.30
PR_{max}	m	0.60	0.60	0.60	0.60	0.60	0.60	0.60	0.60	0.60	0.60
$F_{exp.\ root}$	-	1.30	1.30	1.30	1.30	1.30	1.30	1.30	1.30	1.30	1.30
TSPR	days	119	119	119	119	119	105	105	105	105	105
HI_o	%	51.0	55.0	54.0	55.0	54.0	48.0	54.0	47.0	50.0	51.0
$LI_{exp.canopy}$	-	0.78	0.56	0.80	0.79	0.58	0.80	0.74	0.72	0.48	0.40
$LS_{exp.\ canopy}$	-	0.00	0.24	0.25	0.24	0.22	0.00	0.02	0.14	0.12	0.00
$F_{exp.\ canopy}$	-	3.00	2.60	5.20	5.20	4.70	3.00	2.60	3.00	2.40	1.60
$LS_{est.}$	-	0.72	0.57	0.69	0.69	0.60	0.72	0.71	0.71	0.68	0.72
$F_{est.}$	-	2.60	3.00	4.10	3.20	3.30	3.10	3.10	3.60	6.00	6.00
$LS_{sen.}$	-	0.70	0.69	0.69	0.69	0.69	0.70	0.58	0.69	0.61	0.61
$F_{sen.}$	-	3.00	2.40	3.00	3.00	2.80	3.00	2.60	3.20	2.00	2.80

θ_{PMP} - permanent wilting moisture; θ_{CC} - moisture in field capacity; θ_S - saturation moisture; Tb_{min} - minimun basal temperature; Tb_{max} - maximum basal temperature; CSD - canopy ground cover; Dp - plant density; WP* - ETo and CO_2 normalised crop water yield; WP - water yield during grain formation; TSE - sowing times to emergence; CC_{max} - maximum canopy cover; CCD - coefficient of growth; CDD - coefficient canopy decline; TSS - senescence seeding time; TSF - flowering sowing time; TCF - flowering length time; TSM - sowing at maturity time; PR_{min} - minimum effective depth of the root; $PR_{maáx}$ - maximun effective depth of the root; $F_{exp.\ root}$ - expansion form factor of the root; TPMR - sowing at maximum root depth time; HI_o - adjusted harvest index; $LI_{exp.\ canopy}$ - lower limit of canopy expansion; $LS_{exp.\ canopy}$ - upper limit of canopy expansion; $F_{exp.\ canopy}$ - water stress form factor for canopy expansion; $LS_{est.}$ - upper limit of soil water depletion for stomatal control; $F_{est.}$ - water stress form factor for stomatal control; LS_{sen} - upper limit of water depletion in the soil for canopy senescence; $F_{sen.}$ - water stress form factor for canopy senescence

$$Bo = 0.01 \cdot Dp \cdot MS \quad (6)$$

$$Yo = \frac{NGE \cdot MCG \cdot Dp \cdot 1.15}{100,000} \quad (7)$$

$$HIo = \frac{Yo}{Bo} \quad (8)$$

$$WP_o = 100 \frac{Yo}{\sum ETc} \quad (9)$$

where:

Bo - observed biomass production, t ha^{-1};
Dp - plant density, plant m^{-2};
MS - dry matter, g $plant^{-1}$;
Yo - observed grain yield, t ha^{-1};
NGE - number of grains per ear;
MCG - mass average of one hundred dry grains, g;
HIo - reference season index, %; and,
WPo - observed crop water productivity, kg m^{-3}.

For management parameters, the model includes irrigation method, the day and the irrigation depth applied in each treatment, salinity, soil fertility and the percentage of soil cover at sowing. For the last, 75% coverage with organic material (crop residues) was considered for all crop seasons, due to the practice of direct sowing. Soil fertility was considered ideal and equal for all irrigation treatments, and salinity was disregarded in this study.

For calibration, the parameters obtained experimentally in the 2015/16 and 2017/18 seasons were used for each irrigation treatment, using the hybrids AG 9025 and AG 8780, with the choice of the first hybrid due to its repetition in the next crop.

Calibration was performed using crop, climate, soil and management data for each irrigation treatment at each site and comparing the simulated results with those observed experimentally. Through trial and error, the known parameters were adjusted and the process repeated in the model, aiming to

minimise as much as possible the difference between simulated and observed data.

Validation was performed by using the data from the other crop seasons and hybrids, keeping the crop parameters adjusted in calibration referred to as "standard" and changing only those referring to the crop development, Dp and HIo, which demonstrates the robustness of the model, requiring few variables to validate it.

The performance of AquaCrop was evaluated based on the most commonly used statistical indicators for simulation models, such as coefficient of determination (R^2), performance index (Id), as proposed by Camargo & Sentelhas (1997), quadratic root mean error (RMSE) and quadratic root mean normalised error (NRMSE), as proposed by Loague & Green (1991), and Nash-Sutcliffe efficiency (NSE), as proposed by Nash & Sutcliffe (1970).

$$R^2 = \left[\frac{\sum_{i=1}^{n} (O_i - \bar{O})(S_i - \bar{S})}{\sqrt{(O_i - \bar{O}) \sum_{i=1}^{n} (S_i - \bar{S})}} \right] \quad (10)$$

$$Id = \left\{ 1 - \left[\frac{\sum_{i=1}^{n} (S_i - O_i)^2}{\sum_{i=1}^{n} \left(|S_i - \bar{O}| + |O_i - \bar{O}| \right)^2} \right] \right\} \left\{ \frac{\sum_{i=1}^{n} (S_i - \bar{S})(O_i - \bar{O})}{\sqrt{\sum_{i=1}^{n} (S_i - \bar{S})^2 \sum_{i=1}^{n} (O_i - \bar{O})^2}} \right\} \quad (11)$$

$$RMSE = \sqrt{\frac{\sum_{i=1}^{n} (S_i - O_i)^2}{n}} \quad (12)$$

$$NRMSE = \frac{1}{\bar{O}} \sqrt{\frac{\sum_{i=1}^{n} (S_i - O_i)^2}{n}} 100 \quad (13)$$

$$NSE = 1 - \left[\frac{\sum_{i=1}^{n} (S_i - O_i)^2}{\sum_{i=1}^{n} (O_i - \bar{O})^2} \right] \quad (14)$$

where:

O_i - observed data;
$\bar{O}$ - average of the observed data;
S_i - simulated data;
$\bar{S}$ - average of the simulated data; and,
n - number of relationships involved.

Results and Discussion

The observed ETc (Table 2) ranged from 466.9 to 519.0 mm, with an average of 490.4 mm, which indicates that it is within the range considered for the state of Rio Grande do Sul, Brazil. Such consideration implies that corn crop needs 412-648 mm of water during its cycle depending on the region, which characterises it as a high-water-demand crop. In ET the model overestimated the values, ranging from 431.0 to 632.7 mm, tending to increase as the irrigation water depths increased up to 100% ETc and behaving contrary to irrigation water depths of ≥125% ETc, except for the crop season 2016/17.

This result reflects the difference between a model simulation of ET, which takes into account canopy development and the partitioning of crop transpiration and soil evaporation, and the simplified method for determining ETc in the field.

However, the partitioning of ET by the models is important in predicting biomass productivity, for example, since it is directly related to crop water productivity and consequently to grain yield. On the other hand, Bello & Walker (2016) considered that this partitioning can result in errors that affect the model's reliability, and that in this sense requires improvements.

Table 2. Estimated crop evapotranspiration (ETc), simulated crop evapotranspiration (ET), rainfall, irrigation and total water applied to the corn crop according to irrigation treatment

Place	Season	%ETc	ETc	ET	Applied water (mm)		
			(mm)		Rainfall	Irrigation	Total
Santiago	2015/16	0	488.5	515.0	1436.1	0.0	1436.1
		50	488.5	567.9	1436.1	85.0	1521.1
		75	488.5	590.1	1436.1	127.0	1563.1
		100	488.5	596.4	1436.1	170.0	1606.1
		125	488.5	593.0	1436.1	212.0	1648.1
	2016/17	0	487.4	431.0	1189.2	0.0	1189.2
		50	487.4	443.0	1189.2	67.0	1256.2
		75	487.4	447.6	1189.2	100.0	1289.2
		100	487.4	451.5	1189.2	134.0	1323.2
		125	487.4	449.7	1189.2	167.0	1356.2
Alegrete	2017/18	0	519.0	439.7	500.0	0.0	500.0
		50	519.0	566.2	500.0	161.0	661.0
		75	519.0	608.3	500.0	241.0	741.0
		100	519.0	632.7	500.0	321.0	821.0
		125	519.0	625.1	500.0	401.0	901.0
	2018/19	0	466.9	455.7	922.2	0.0	922.2
		50*	466.9	523.5	922.2	54.0	976.2
		75*	466.9	546.6	922.2	81.0	1003.2
		100*	466.9	588.7	922.2	107.0	1029.2
		100	466.9	564.3	922.2	178.0	1100.0

* - Suppressed irrigation water depths by 50% in the reproductive period of de crop

The rainfall during the crop seasons were higher than the evaporative demand of the crop, except for the crop season 2017/18. However, its poor distribution, which is characteristic of the region, justifies supplementary irrigation in periods critical for water deficit, which correspond to the grain filling, and compensating for poor supply (Minuzzi & Lopes, 2015). In this sense, 6, 7, 18 and 10 irrigations were performed for the four crop season's, but for the critical period 0, 2, 2 and 4 irrigations were performed, respectively.

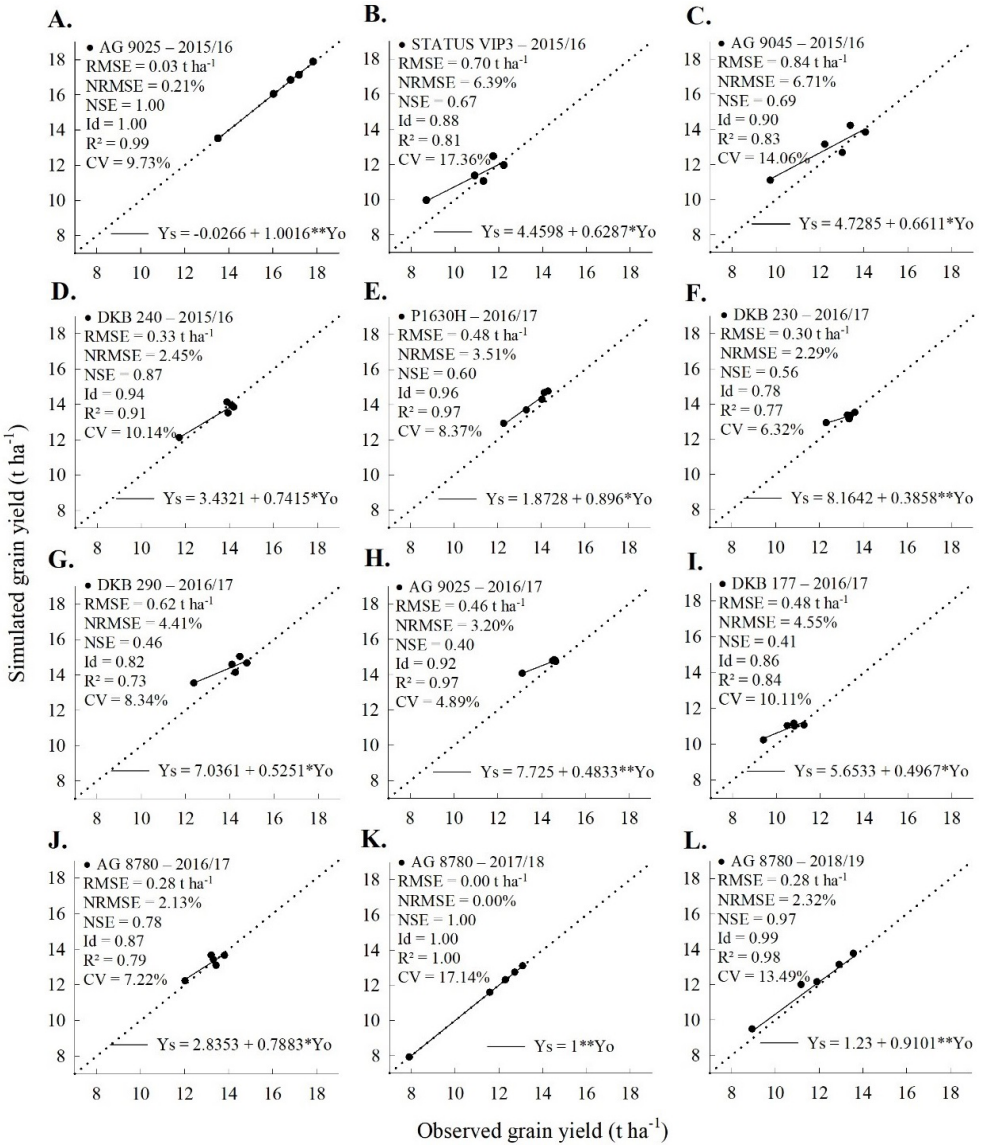
The best results for model performance were obtained in calibration, being more accurate for the hybrid AG 8780 (Figure 2K), followed by the hybrid AG 9025 (Figure 2A).

In validation, the most outstanding hybrids were: AG 8780 (Figure 2L), P1630H (Figure 2H), DKB 240 (Figure 2D), AG 9025 (Figure 2E) and AG 9045 (Figure 2C), which were classified as "excellent", followed by the hybrids Status VIP3 (Figure 2B), AG 8780 (Figure 2I), DKB 177 (Figure 2F) and DKB 290 (Figure 2G), which were classified as "optimal", and DKB 230 (Figure 2J), classified as "very good", jointly describing the accuracy and precision of the AquaCrop model.

R^2 ranged from 0.73 to 0.98, which describes a good fit between acceptable data. However, as it only quantifies dispersion, it can imply good results but not distinguish between underestimation and overestimation from the results. The RMSE, which provides the overall performance of the model and synthesises the average difference between the observed and simulated model data, ranged from 0.03 to 0.0 t ha^{-1}.

According to Loague & Green (1991), RMSE values are always positive and vary from 0 to ∞: the closer to 0, the better the model fit. The NRMSE, which provides the relative difference between the observed data and that simulated by the model, presented an "excellent" classification (NRMSE < 10%) for all hybrids.

The NSE, which describes how well the observed and simulated data fit the 1:1 scatter plot line and indicates the robustness and efficiency of the model (Silva et al., 2018),



• - Hybrid and crop season; Id - performance index; RMSE - quadratic root mean error; NRMSE - quadratic root mean normalised error; NSE - Nash-Sutcliffe efficiency; Ys - Simulated grain yield; Yo - grain yield; * - Significant at $p \leq 0.05$ by F-test, ** - Significant at $p \leq 0.01$ by F-test

Figure 2. Grain yield observed and simulated by the AquaCrop model for different corn hybrids, crop seasons and study locations: AG 9025 - 2015/16 (A), STATUS VIP 3 - 2015/16 (B), AG 9045 - 2015/16 (C), DKB 240 - 2015/16 (D), AG 9025 - 2016/17 (E), DKB 177 - 2016/17 (F), DKB 290 - 2016/17 (G), P1630H - 2016/17 (H), AG 8780 - 2016/17 (I), DKB 230 - 2016/17 (J), AG 8780 - 2017/18 (K), AG 8780 - 2018/19 (L)

ranged from 0.40 to 1.0. According to Moriasi et al. (2007), NSE values range from -∞ to 1.0, with values between 0 and 1.0 being considered as indicating acceptable performance and 1.0 denoting optimal performance.

Although the simulations presented different performances for the hybrids, the results were satisfactory and demonstrated the applicability of the model, since the "standard" parameters were used for all hybrids in the respective locations. The same was described by Ran et al. (2018), indicating that AquaCrop, even if producing some inaccurate estimates, has several advantages, such as the use of the same parameters for different varieties without the need for individual calibration, which makes it a widely applicable model.

Regarding irrigation treatments, the model performance was "excellent"; however, it overestimated grain yield for the less irrigated treatments (0, 50 and 75% ETc), this being more evident in the rainfed condition (0% ETc), and underestimated for more irrigated treatments (100 and 125% ETc). The results of this study and those reported in the literature indicate that the performance of the AquaCrop model declines in conditions of water stress (Sandhu & Irmak, 2019).

Studies with the AquaCrop model for the production of crops such as corn (Heng et al., 2009) showed that the best performance of the model is seen with total irrigation or with mild water deficit, with less satisfactory performance as a result of extreme deficits or under rainfed conditions. The results of treatment with 0% ETc were also in agreement with Ahmadi et al. (2015) who obtained RMSE and NRMSE of 800 kg ha^{-1} and 15.2%, respectively, for Zimbabwe.

In the 100 and 125% ETc treatments, the differences were reduced, in agreement with García-Vila & Fereres (2012), who also obtained an RMSE of 0.25 t ha^{-1} in the calibration of the AquaCrop model for corn subjected to total irrigation in Spain. However, in the 50 and 75% ETc treatments, the differences were again high, demonstrating some inaccuracy of the model in simulating deficits that occurred throughout the crop season cycle, and more accurate in conditions without deficit.

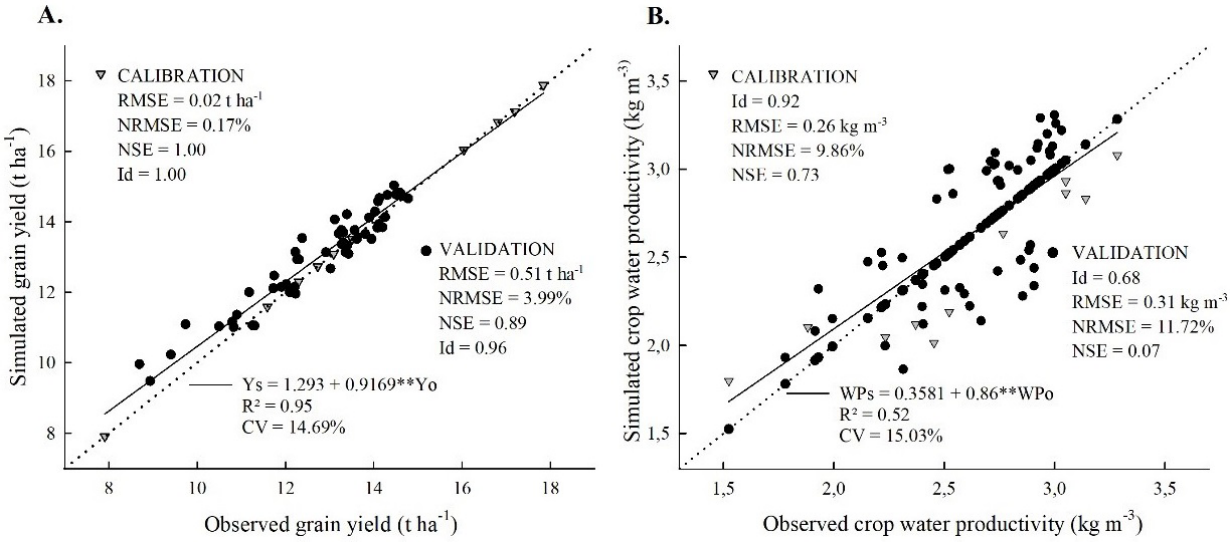
Similar results were obtained by Kumar et al. (2018), who, when evaluating the performance of AquaCrop for corn irrigated with water depths of 0, 50, 75 and 100% of ETc, observed a decreasing linear behaviour from 0 to 100% ETc. However, the performance maintained within satisfactory agreement with Heng et al. (2009) who, by obtaining an RMSE of 0.8 t ha^{-1} and an NRMSE of 5.61%, concluded that the AquaCrop model predicts crop yield very well under full irrigation or moderate stress.

According to the general performance of the AquaCrop model, it is possible to consider that suppression of the irrigation depth by 50% ETc during the reproductive period of the crop resulted in satisfactory performance. This indicates that the water deficit imposed in this period did not reflect discrepant differences in the simulation and is in agreement with Gebreselassie et al. (2015), who found that simulated yield (Ys) is lower when the deficit occurs in the vegetative phase, except in the initial phase, than when it occurs in the reproductive and maturation phases.

The results obtained imply that the AquaCrop model does not present adjusted stress coefficient values and that this produces problems in soil water modelling that are later translated into biomass production (B) and yield simulations containing errors in severe water-deficiency situations Giménez (2019).

By analysing the hybrid AG 8780, which produced an average of 13.16, 12.52 and 11.95 t ha^{-1} in the last three crop seasons, there was increasing linear variation in the total water applied. The same was observed by Donfack et al. (2018) when evaluating the water required by corn cultivation using the AquaCrop model, who observed decreasing production variation as a function of crop season, indicating that climatic variability (precipitation) and irrigation influence corn yield.

The overall performance of the grain yield in the calibration and validation of the AquaCrop model (Figure 3A) was "excellent", correlating the data efficiently and satisfactorily. Furthermore, the model results agree with those reported by other authors in similar studies, such as Oiganji et al. (2016) who obtained RMSE and NSE values of 0.32 t ha^{-1} and 0.82, respectively, in northern Nigeria, and Giménez (2019), who obtained RMSE, NRMSE and Id values of 0.84 t ha^{-1}, 6.9% and 0.96, respectively, in Uruguay.



Id - Performance index; RMSE - Quadratic root mean error; NRMSE - Quadratic root mean normalised error; NSE - Nash-Sutcliffe efficiency; Ys - Simulated grain yield; WPs - Simulated crop water productivity; WPo - Observed crop water productivity; ** - Significant at p ≤ 0.01 by F-test

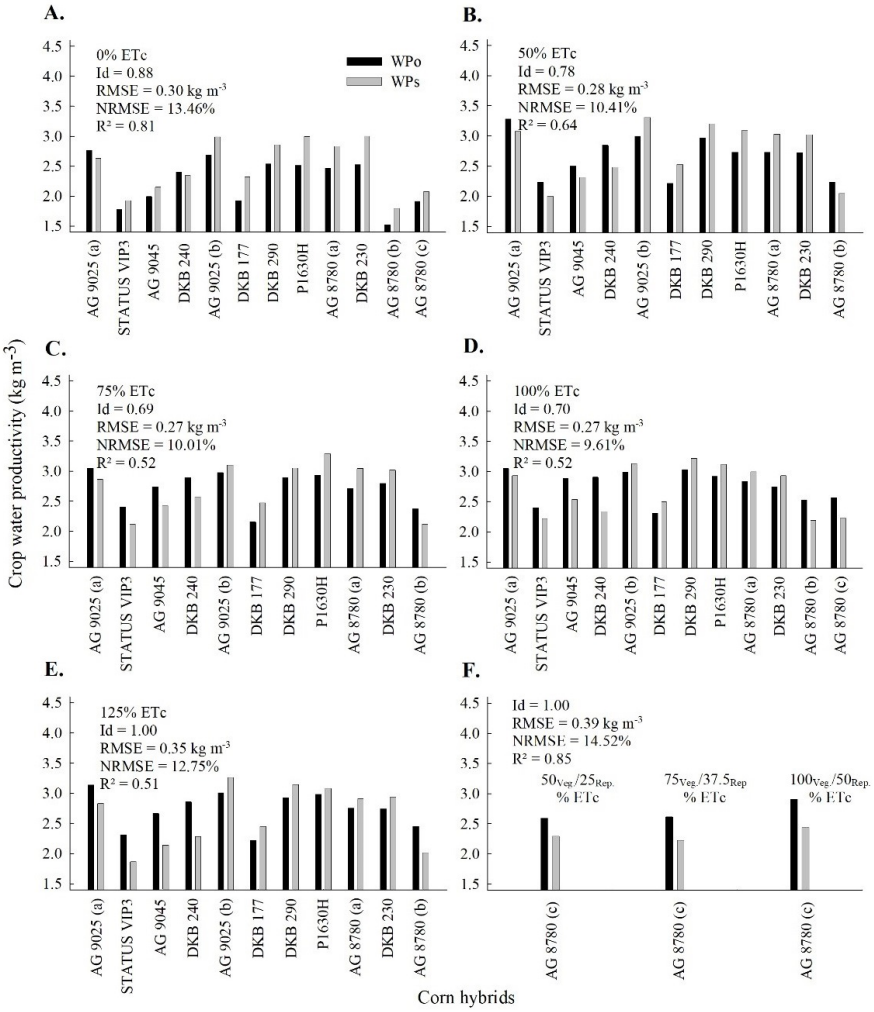
Figure 3. General performance of grain yield (A) and crop water productivity (B) in the calibration and validation of the AquaCrop model

Despite the excellent overall performance of the AquaCrop model (Figure 3A), it is noted that for the lowest grain yields (up to 10 t ha^{-1}) there is a greater distance from the 1:1 line. This indicates an overestimation by the model when simulating severe water-deficit situations, since these grain yields were observed in the lowest irrigation treatments, as already observed in Figure 2. Similar observations were described by Heng et al. (2009) for corn, concluding that the model overestimates under deficit conditions and underestimates under irrigation conditions. In this case, Heng et al. (2009) suggested that simulations under water-deficit conditions could be improved in the model by adjustments to conservative parameters or those considered standard, which would make it more sensitive to these conditions.

The crop water productivity (WP; Figure 3B) showed "excellent" performance for calibration and "good" for validation of the AquaCrop model. However, there was a discrepancy between the observed and simulated values, implying a low efficiency (NSE = 0.07) in validation, resulting in a low R^2, and a tendency to overestimation in the model. This explains why, for the calculation of the observed crop water productivity (WPo), the ETc was used for all irrigation and hybrid treatments in their respective crop seasons. In the AquaCrop model, ET is simulated for each situation, which takes into account canopy development and partitioning of crop transpiration and soil evaporation. In this sense, genetic differences between hybrids, environmental conditions, excessive drainage simulation (not observed in the field) or a possible spatial variability in the soil may have interfered with the deviations introduction in the results.

The ET partitioning is important in predicting simulated biomass production (BS), as it is related directly to WP and, consequently, to grain production. However, Bello & Walker (2016) considered that this partitioning may introduce errors that reduce the reliability of the model, and that, in this sense, needs improvement. However, the results are in agreement with those of Díaz-Pérez et al. (2018) who, studying AquaCrop model for corn and soybean, observed differences between observed (WPo) and simulated (WPs) crop water productivity that can result in overestimation of 15-55% and associated them with miscalculations when using simplified methods to determine ETc in the field.

The average results of WPo, WPs and their differences in the four crop seasons (Figure 4) ranged from 2.22 to 2.71 kg m^{-3}, 2.03 to 2.69 kg m^{-3}, and 0.19 to 0.36 kg m^{-3}, respectively, behaving in parallel with the increase in precipitation volume.



Id - performance index; RMSE - quadratic root mean error; NRMSE - quadratic root mean normalised error; $50_{Veg.}/25_{Rep.}$%, $75_{Veg.}/37.5_{Rep.}$%; $100_{Veg.}/50_{Rep.}$%; AG 9025(a) - crop season 2015/16; AG 9025(b) - crop season 2016/17; AG 8780(a) - crop season 2016/17; AG 8780(b) - crop season 2017/18; AG 8780(c) - crop season 2018/19

Figure 4. Crop water productivity observed (WPo) and simulated (WPs), for corn hybrids in different crop seasons and irrigation treatments: 0% (A); 50% (B), 75% (C), 100% (D), 125% ETc (E); and suppressed irrigation water depths in the reproductive period (F)

The lowest values of WPo and WPs were obtained in the 2017/18 crop season, with a precipitation of 500 mm, which, on the other hand, presented the highest ETc. The reduction in crop water productivity at high values of ETc is partly justified by the loss of water by evaporation or an increase in nutrient leaching. In contrast, higher crop water productivity values were observed under conditions without water or nutrient stress (Araya et al., 2017).

For irrigation treatments (Figure 4), WPo and WPs values ranged from 2.25 to 2.84 and 2.52 to 2.73 kg $ha^{-1,}$ showing satisfactory performance.

The 100 and 50% ETc treatments, with irrigation water depth suppression in the reproductive period (Figure 4), were classified as "excellent". The 0% ETc (Figure 4A) treatment was classified as "great", followed by "very good" for 50 and 100% ETc, and "good" for 75%.

The WPs were apparently better in the 75% ETc treatment compared to the simulated grain yield (Ys; 13.85 t ha^{-1}) and 100% ETc treatment (13.83 t ha^{-1}), representing water savings with no reduction in production. The results are similar to those of Zhao et al. (2019), who obtained better WPs in the 75% ETc treatment and concluded that lower ETc percentages are effective in saving water while maintaining yield level.

Conclusion

The AquaCrop model can be used to estimate grain yield and water productivity of a corn crop in the study region, as it is efficient and applicable to different hybrids, crop seasons and irrigation strategies.

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Literature Cited

Ahmadi, S. H.; Mosallaeepour, E.; Kamgar-Haghighi, A. A.; Sepaskhah, A. R. Modeling maize yield and soil water content with AquaCrop under full and deficit irrigation managements. Water Resource Management, v.29, p.2837-2853, 2015. https://doi.org/10.1007/s11269-015-0973-3

Albuquerque, P. E. P de; Resende, M. Irrigação: manejo de irrigação. In: Cruz, J. C. (ed.). Cultivo do milho. 5.ed. Sete Lagoas: Embrapa Milho e Sorgo, 2009.

Allen, R. G.; Pereora, L. S.; Raes, D.; Smith, M. Crop Evapotranspiration: Guidelines for computing crop water requirements. Food and Agriculture Organization, Irrigation and drainage paper 56. Rome, 1998. 300p.

Araya, A.; Kisekka. I.; Vara Prasad, P. V.; Gowda, P. H. Evaluating Optimum Limited Irrigation Management Strategies for Corn Production in the Ogallala Aquifer Region. Journal Irrigation Drainage Engineering, v.143, 2017. https://doi.org/10.1061/%28ASCE%29IR.1943-4774.0001228

Bello, Z. A.; Walker, S. Calibration and validation of AquaCrop for pearl millet (*Pennisetum glaucum*). Crop Pasture Science, v.67, p.948-960, 2016. https://doi.org/10.1071/CP15226

Bergamaschi, H.; Dalmago, G. A.; Bergonci, J. I.; Bianchi, C. A. M.; Müller, A. G.; Comiran, F.; Heckler, B. M. M. Distribuição hídrica no período crítico do milho e produção de grãos. Pesquisa Agropecuária Brasileira, Brasília, v.39, p.831-839, 2004.

Camargo, A. P.; Sentelhas, P. C. Avaliação do desempenho de diferentes métodos de estimativa da evapotranspiração potencial no Estado de São Paulo, Brasil. Revista Brasileira de Agrometeorologia, v.5, p.89-97, 1997.

Cruz, J. C.; Pereira Filho, I. A.; Borghi, E.; Simão, E. de P. Quatrocentos e setenta e sete cultivares de milho estão disponíveis no mercado de sementes do Brasil para a safra 2015/16. Sete Lagoas: Embrapa Milho e Sorgo, 2015. 28p.

Díaz-Pérez, Y.; Villalobos-Pérez, M. A.; González-Robaina, F.; Herrera-Puebla, J. Validación del modelo AquaCrop en maíz (*Zea mays* L.) y sorgo (*Sorgum vulgare* L. Monech). Revista Ingeniería Agrícola, v.8, p.3-10, 2018.

Donfack, F. C.; Lenouo, A.; Tchawoua, C. Water Requirements for Corn Yields in the Northern Regions of Cameroon Using AquaCrop Model. Journal of Agriculture and Ecology Research International, v.16, p.1-11, 2018. https://doi.org/10.9734/JAERI/2018/44993

Doorenbos, J.; Kassam, A. Yield response to water. Irrigation and Drainage Paper n. 33. FAO, Rome, 1979. 193p.

Doorenbos, J.; Kassam, A.H. Efeito da água no rendimento das culturas. Rome: FAO, 1994. 306p.

García-Vila, M.; Fereres, E. Combining the simulation crop model AquaCrop with an economic model for the optimization of irrigation management at farm level. European Journal of Agronomy, v.36, p.21-31, 2012. https://doi.org/10.1016/j.eja.2011.08.003

Gebreselassie, Y.; Ayana, M.; Tadele, K. Field-experimentation-based simulation of yield response of maize crop to deficit irrigation using AquaCrop model, Arba Minch, Ethiopia. African Journal of Agricultural Research, v.10, p.269-280, 2015. https://doi.org/10.5897/AJAR2014.8703

Giménez, L. Aquacrop model evaluation in maize under different water availabilities in the western of Uruguay. International Journal of Plant, Animal and Environmental Sciences, v.9, p.103-117, 2019. http://doi.org/10.21276/ijpaes

Heng, L. K.; Hsiao, T.; Evelt, S.; Howel, T.; Stetuto, P. Validating the FAO AquaCrop model for irrigated and water deficient field maize. Agronomy Journal, v.101, p.488-498, 2009. https://doi.org/10.2134/agronj2008.0029xs

Hsiao, T. C.; Heng, L.; Steduto, P.; Rojas-Lara, B.; Raes, D.; Fereres, E. AquaCrop - The FAO crop model to simulate yield response to water: III. Parameterization and testing for maize. Agronomy Journal, v.101, p.448-459, 2009. https://doi.org/10.2134/agronj2008.0218s

Kumar, V.; Chandra, R.; Jain, S. K. Performance evaluation of AquaCrop model for rabi maize Crop in the north Bihar condition. Journal of Pharmacognosy and Phytochemistry, v.7, p.973-979, 2018.

Loague, K.; Green, R. E. Statistical and graphical methods for evaluating solute transport models: Overview and application. Journal of Contaminant Hydrology, v.7, p.51-73,1991. https://doi.org/10.1016/0169-7722(91)90038-3

Minuzzi, R. B.; Lopes, F. Z. Desempenho agronômico do milho em diferentes cenários climáticos no Centro-Oeste do Brasil. Revista Brasileira de Engenharia Agrícola e Ambiental, v.19, p.734-740, 2015. https://doi.org/10.1590/1807-1929

Moriasi, D.; Arnold, J.; Van Liew, M.; Bingner, R.; Harmel, R.; Veith, T. Model evaluation guidelines for systematic quantification of accuracy in watershed simulations. Transactions of the ASABE, v.50, p.885-900, 2007. https://doi.org/10.13031/2013.23153

Nash, J. E.; Sutcliffe, J. V. River flow forecasting through conceptual models Part I - A discussion of principles. Journal of Hydrology, v.10, p.282-290, 1970. https://doi.org/10.1016/0022-1694(70)90255-6

Oiganji, E.; Ignadun, H. E.; Mudiare, O. J.; Oyebode, M. A. Calibrating and validating AquaCrop model for maize crop in Northern zone of Nigeria. Agricultura Engineering International, v.18, p.1-13, 2016.

Pizolato Neto, A.; Camargos, A. E. V.; Valeriano, T. B.; Sgobi, M. A.; Santana, M. J. de. Doses de nitrogênio para cultivares de milho irrigado. Nucleus, v.13, p.87-96, 2016. https://doi.org/10.3738/1982.2278.1606

Raes, D.; Steduto, P.; Hsiao, T. C.; Fereres, E. AquaCrop - The FAO crop model to simulate yield response to water: II. Main algorithms and software description. Agronomy Journal, v.101, p.438-447, 2009. https://doi.org/10.2134/agronj2008.0140s

Ran, H.; Kang, S.; Li, F.; Du, T.; Tong, L.; Li, S.; Ding, R.; Zhang, X. Parameterization of the AquaCrop model for full and deficit irrigated maize for seed production in arid Northwest China. Agricultural Water Management, v.203, p.438-450, 2018. https://doi.org/10.1016/j.agwat.2018.01.030

Sandhu, R.; Irmak, S. Performance of AquaCrop model in simulating maize growth, yield, and evapotranspiration under rainfed, limited and full irrigation. Agricultural Water Management, v.223, p.1-15, 2019. https://doi.org/10.1016/j.agwat.2019.105687

Silva, V. de P. R. da; Silva, R. A.; Maciel, G. F.; Braga, C. C.; Silva Júnior, J. L. C. da; Souza, E. P. de; Almeida, R. S. R.; Silva, M. T.; Holanda, R. M. de. Calibration and validations of the AquaCrop model for the soybean crop grow under diferent levels of irrigation in the Motopiba region, Brazil. Revista Ciência Rural, v.48, p.1-8, 2018. https://doi.org/10.1590/0103-8478cr20161118

Steduto, P.; Hsiao, T. C.; Raes, D.; Fereres, E. AquaCrop-The FAO crop model to simulate yield response to water: I. Concepts and underlying principles. Agronomy Journal, v.101, p.426-437, 2009. https://doi.org/10.2134/agronj2008.0139s

Twumasi, G. B.; Junaid, A. M.; Shin, Y.; Choi, K. S. Prediction of corn yield based on different climate scenarios using AquaCrop model in Dangme East District of Ghana. Journal of the Korean Society of Agricultural Engineers, v.59, p.71-79, 2017. https://doi.org/10.5389/KSAE.2017.59.1.071

Zhao, J.; Xue, Q.; Hao, B.; Marek, T. H.; Jessup, K. E.; Xu, W.; Bean, B. W.; Colaizzi, P. D. Yield determination of maize hybrids under limited irrigation. Journal of Crop Improvement, v.33, p.410-427, 2019. https://doi.org/10.1080/15427528.2019.1606129