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AquaCrop model assessment for simulating soybean response under water stress

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ABSTRACT: Lately, irrigated soybean production has increased; therefore, tools that can aid water resources management must be improved. Two experiments were carried out, the first one from May to August and the second one from September to December 2019. The experimental design included randomized blocks with five treatments and four replicates. In the control treatment (SE), irrigation was carried out to meet the crop's water demand during all growth stages. In the other treatments, irrigation was interrupted at specific crop growth stages (TI = VC-V4, TII = V5-R1, TIII = R1-R5, and TIV = R5-R7), and then restored. After calibration, the model satisfactorily estimated the canopy cover, biomass, and soybean yield, with high values of determination coefficients ($r^2 > 0.90$), low RMSE and MBE values, and high values of EF. In experiment 1, the soil water content was overestimated in the SE, TI, and TIV treatments by 0.24%, 0.78%, and 0.23%, respectively, and underestimated by 3.3% and 5.5% in the TII and TIII treatments, respectively. In experiment 2, in the SE, TI, TII, TIII, and TIV treatments, the soil water content was underestimated by 6%, 3%, 4.6%, 5.9%, and 6.7%, respectively. Real evapotranspiration was overestimated in all treatments in both experiments, with low r^2 values in both experiments 1 (0.11– 0.23) and 2 (0.04 – 0.21).
Key words: agricultural management, irrigation management, soil water content modelling, crop evapotranspiration.

Avaliação do modelo AquaCrop para simulação da resposta da soja sob estresse hídrico

RESUMO: Ultimamente, a produção de soja irrigada tem aumentado, portanto, ferramentas que auxiliem na gestão dos recursos hídricos devem ser aprimoradas. Foram realizados dois experimentos, o primeiro de maio a agosto e o segundo de setembro a dezembro de 2019. O delineamento experimental foi em blocos casualizados com cinco tratamentos e quatro repetições. No tratamento testemunha (SE), a irrigação foi realizada para atender a demanda hídrica da cultura durante todas as fases de crescimento. Nos demais tratamentos, a irrigação foi interrompida em determinados estádios de desenvolvimento da cultura (TI = VC-V4, TII = V5-R1, TIII = R1-R5 e TIV = R5-R7) e, a seguir, restabelecida. Após a calibração, o modelo estimou satisfatoriamente a cobertura do dossel, a biomassa e a produtividade da soja, com altos valores de coeficientes de determinação ($r^2 > 0,90$), baixos valores de RMSE e MBE e altos valores de EF. No experimento 1, o teor de água do solo foi superestimado nos tratamentos SE, TI e TIV em 0,24%, 0,78% e 0,23%, respectivamente, e subestimado em 3,3% e 5,5% nos tratamentos TII e TIII, respectivamente. No experimento 2, nos tratamentos SE, TI, TII, TIII e TIV, o teor de água no solo foi subestimado em 6%, 3%, 4,6%, 5,9% e 6,7%, respectivamente. A evapotranspiração real foi superestimada em todos os tratamentos em ambos os experimentos, com baixos valores de r^2 em ambos os experimentos 1 (0,11– 0,23) e 2 (0,04 – 0,21).
Palavras-chave: manejo agrícola, manejo de irrigação, modelagem do teor de água no solo, evapotranspiração de culturas.

INTRODUCTION

In the Brazil soybean is typically grown under rainfed conditions (DA SILVA et al., 2019). However, irrigated soybean has been expanding, mainly in the Cerrado region, which concentrates about 80% of the central pivots (ALTHOFF & RODRIGUES, 2019), increasing the water demand in this region, which already faces water problems in some of its main hydrographic basins. Considering the current water use scenario and the increase in disputes over the use of water resources, irrigation increases areas must be properly planned.

When evaluating scenarios to establish water management strategies in watersheds, computational models are valuable tools that allow the manager to see the results of the simulations before making a decision. In a strategy of developing simpler and fewer data demanding models, AquaCrop (RAES et al., 2022) has been widely used. This model was developed to estimate crop yield, water demand, and water productivity under water deficit conditions,

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with biophysical processes simplified so the amount of data required for entry and calibration remains limited, while robustness and accuracy are protected, which aids its use, especially in regions with low data availability, such as the Brazilian cultivation soybean areas (TERÁN-CHAVES et al., 2022).

The AquaCrop model has been applied in several regions of the world under different climatic and agronomic conditions. It has been used to identify crop response to water stress (RAES et al., 2023) and improve irrigation management (GARCIA-VILA et al., 2019). Although, the model has been applied in several regions of the world, it has hardly been applied in the Brazilian cultivation soybean areas. Also, the authors of this study are unaware of studies that evaluated the AquaCrop model to estimate yield in crops whose water deficit was applied by growth stages. Thus, the present research evaluated the AquaCrop model for soybean grown under water deficit applied at specific growth stages.

MATERIALS AND METHODS

Experimental area

The experiments were conducted from May to August and from October to December 2019 with the soybean variety BRS 7581RR (undetermined type). The experiments were undertaken at the Agricultural Research Center of the Cerrado (Embrapa Cerrados), located in the Central Plateau region of the Cerrado Biome (15 ° 35'55.1 "S, 47 ° 42'27.4 "W), Planaltina – DF, Brazil.

The region's climate is classified as Aw (Köppen, 1948), with average air temperature equal to 22 °C and rainfall of 1,500 mm year $^{-1}$ concentrated between October and March. The meteorological data, necessary for the experiment, was obtained from a climatological station located about 2 km from the experiment. The soil in the area is classified as Red Latosol, containing 58% clay. Its average values of global density (Gd), permanent wilting point (PWP), and field capacity (FC) in layers 0-20 cm and 20- 40 cm is Gd = 1.09 g cm $^{-3}$, PWP = 0.23 cm ^{3} cm $^{-3}$ and FC = 0.35 cm ^{3} cm $^{-3}$, respectively.

Crop management

The crop seeds were sown with a spacing of 0.5 m between rows and 18 plants per linear meter, aiming to reach the density of 360,000 plants per hectare. Fertilization was carried out in the sowing pit in the following quantities: 22.5 kg of N; 112.5 kg of P_2O_5, and 112.5 kg of K_2O per hectare following soil chemical analysis and recommendations by Sousa and Lobato (2004). A subsurface irrigation system was used. The system consisted of a lateral drip, buried at 28 cm, and emitters spaced at 0.9 m x 0.4 m, with initial emitter pressure of 20 mca and flow of 2 L h $^{-1}$. Experiment 1 was sown on 05/06/2019 and harvested on 08/09/2019. The second experiment (experiment 2), used to validate the model, was sown on 09/09/2019 and harvested on 12/25/2019. Experiment 1 was carried out in the dry season, when soybeans are generally not cultivated in the region for sanitary reasons, but it is the time when the effect of water deficit with controlled irrigation can be verified and for this reason the experiment was implemented at that time. Experiment 2 was carried out in the rainy season, in the appropriate planting window for the region.

Experimental design

The experiments were conducted in a randomized block design, with four replications (4 m x 2 m) and five treatments (9 m x 20 m), totalling twenty experimental plots. In the control treatment (SE), irrigation was complete at all growth stages, this means that the irrigation managed to supply all the crop water demand in all growth stages. In the other treatments, irrigation was suspended in certain phenological phases of the crop. Irrigation was suspended only for the duration of that phase. After the phenological phase was completed, irrigation was restored according to the control treatment. The following phenological phases were considered to assess the impact of water deficit: VC-V4 (TI); V5-R1 (TII); R1-R5 (TIII); and R5-R7 (TIV). For instance, in the TI treatment, irrigation was completely suspended from the beginning of the VC phenological phase to the beginning of the V5 phase, after which irrigation was restored. For clearer understanding, from now on, water deficit treatment means treatment in which irrigation was suspended. The crop's phenological stages were identified through the morphological evaluation of the plant in the field.

Irrigation management and soil moisture measurement

Applied irrigation depth was calculated based on the current soil moisture in each treatment, using Equation 1. The depth of the crop's root system was evaluated weekly in each treatment. In order to do this, three plants were randomly removed in the area of each experimental unit and maximum root length was measured. Irrigation was applied whenever soil moisture measured in the root zone reached 50% of total water available in the soil. Soil moisture was determined using the gravimetric method. Soil samples were taken daily in layers of 0-20 and 20-40 cm in each experimental plot, then they were weighed and dried in a heating chamber at 105 °C for 24h. After drying, the soil samples were weighed again. After having the soil's wet and dry weight, current soil moisture was obtained, and irrigation depth to be applied in each treatment was calculated.

$$AI = \frac{0.1\ (\theta_{CC} - \theta_{actual})}{Ef}\ Gd\ Z \qquad (1)$$

in which

AI - applied irrigation depth, mm

θ_{CC} - soil moisture at field capacity, %;

θ_{actual} - current soil moisture in each treatment, %;

Gd - global soil density, g cm $^{-3}$;

Z – crop's root system depth, cm;

Ef - Efficiency of the irrigation system (Ef = 0.90).

Calculating the real evapotranspiration

The actual evapotranspiration (ETa) for each growth stage evaluated in all treatments was estimated using the soil water balance approach through the collected values of soil moisture (ALLEN et al., 1998):

$$ETa = P + I + CR - D - R \pm \Delta S \qquad (2)$$

where

P = precipitation, mm;

I = irrigation depth, mm;

CR = capillary rise, mm;

D = deep percolation, mm;

R = surface runoff, mm;

ΔS = soil water storage variation in the plant rooting depth, mm.

Deep percolation was considered zero, because irrigation was applied only in the layer corresponding to the root system of the crop (0.0-0.40 m). Surface runoff was ignored because the irrigation system used was subsurface drip. The capillary rise of the water table was ignored because the study site had no drainage and salinity problems.

Biomass and grain yield estimation

Four biomass assessments were carried out for experiment 1 (45, 55, 69, and 83 DAS) and experiment 2 (57, 65, 81, and 100 DAS), by removing the plants inside a 0.5 m line in the planting line, in the four replicates. After removing the plants, the root, stem, leaves, and pods were separated, packed in paper bags, and then taken to a heating chamber, in which they were dried for 36h at a temperature of 75 °C, and later were weighed. The grain yield analyses were made by randomly selecting an area, in each replicate, and removing all plants in two linear meters. The pods, of each plant, were stripped and the grains were properly packed in identified paper bags and sent to the seed analysis laboratory. There, they were weighed on an analytical scale, and after correcting the grain moisture to 13%, the yield was determined in each treatment.

Model input data description

To use AquaCrop it is necessary to input data on climate, crop characteristics, soil, and a description of the management practices. The AquaCrop uses a normalized function of the crop water productivity to estimate biomass. The equation for the estimation of the final biomass proposed by STEDUTO et al. (2009) is shown in Equation 3.

The AquaCrop model estimates potential yield based on the amount of water the crop transpires under different water availability regimes. Yield calculation is done by adjusting the harvest index as a function of the water stress applied at the beginning of yield formation, flowering and during yield formation, as shown in Equation 4 (STEDUTO et al., 2009).

$$B = WP \sum T_r \qquad (3)$$

$$Y = HI_o\ B \qquad (4)$$

where

B = aboveground biomass, kg m $^{-2}$

WP = normalized water productivity, kg m $^{-2}$

Tr = crop transpiration, mm.

Y = yield, kg m $^{-2}$

HIo = reference harvest index, %.

The model estimates the canopy cover (CC) development, based on the initial CC value, on the canopy growth coefficient (CGC), on the maximum CC value, on the canopy decline coefficient (CDC), and the number of days for emergency and senescence/maturity.

The CC curve can be parameterized using the leaf area values measured in the field. The CC values, through the leaf area index (LAI) data, were calculated using the Equation 5 developed by HSIAO et al. (2009).

$$CC = 1.005\ (1 - \exp\ (-0.6\ LAI)^{1.2} \qquad (5)$$

The leaf area was evaluated every two weeks. Four plants, in each of the four replicates of the five treatments, were removed and taken to the laboratory where the leaf area was measured using an LI-3100c leaf area meter (Licor, Inc., Lincoln, NE, EUA).

The meteorological data (temperature and rainfall) required by the model were obtained from a weather station located about 2 km from the experiment. The reference evapotranspiration (ET0) was calculated using the FAO-Penman Monteith (ALLEN et al., 1998). For all treatments, a default file of the average annual CO_2 concentration, measured at the Mauna Loa Observatory in Hawaii and provided by AquaCrop, was used.

The model's initial parameters were selected from a default soybean file presented by RAES et al. (2012). Default values were used for the parameters not measured in the experiment. A culture file (.CRO) was created after calibration. Irrigation data from the water deficit treatments was used to determine the crop response to water stress. Stress caused by salinity and soil fertility was not considered. The crop phenology was observed on calendar days and later converted to thermal time (GDD).

A single soil file (.SOL) was created and used in each experiment. Irrigation took place through a buried drip irrigation system therefore; the soil surface was not damp. Five separate irrigation files (.IRR) were created for each treatment. For the field management file (.MAN), soil fertility was not limiting, and the soil surface did not contain any mulch nor presented practices to prevent runoff.

Model calibration and validation

The model was calibrated with the data from the SE treatment of experiment 1. Model validation was performed using the observed data of yield, biomass, and real evapotranspiration of all treatments in experiment 2. Table 1 shows the default values of the parameters used (RAES et al., 2012), as well as the parameter values calibrated in experiment 1.

The estimated values were compared with the observed ones in the experiments, and statistics of the model performance of the validation were analyzed. The statistics indicators used to assess model performance were the root mean square error (RMSE), mean bias error (MBE), model efficiency of Nash-Sutcliffe (EF), and the determination coefficient (r^2). The indicators were calculated through equations 6, 7, 8, and 9.

$$\mathrm{RMSE} = \sqrt{\frac{1}{n}\sum_{i=1}^{n}(P_i - O_i)^2} \tag{6}$$

$$\mathrm{MBE} = \bar{P}_i - \bar{O}_i \tag{7}$$

$$\mathrm{EF} = 1 - \frac{\sum_{i=1}^{n}(P_i - O_i)^2}{\sum_{i=1}^{n}(O_i - \bar{O})^2} \tag{8}$$

$$r^2 = \frac{\left(\sum_{i=1}^{n}(P_i - \bar{P}_i)(O_i - \bar{O}_i)\right)^2}{\sum_{i=1}^{n}(P_i - \bar{P}_i)^2 \ \sum_{i=1}^{n}(O_i - \bar{O})^2} \tag{9}$$

Table 1 - Soybean parameters calibrated through experiment 1 and default of the AquaCrop model used in this study.

Parameters	Calibrated	Default
Base temperature (°C)	10	5
Cut-off temperature (°C)	30	30
Canopy cover at 90% emergence (cm^2 $plant^{-1}$)	5	5
Maximum effective rooting depth (m)	0.4	2
Maximum basal crop coefficient (Kcb)	0.9	1.1
Water productivity (g m^{-2})	17	15
Soil water depletion factor for canopy expansion - Upper threshold	0.20	0.15
Soil water depletion factor for canopy expansion - Lower threshold	0.55	0.65
Shape factor for water stress coefficient for canopy expansion	3	3
Soil water depletion fraction for stomatal control - Upper threshold	0.60	0.60
Shape factor for water stress coefficient for stomatal control	3	3
Soil water depletion factor for canopy senescence - Upper threshold	0.85	0.7
Shape factor for water stress coefficient for canopy senescence	3	3
Vol% for Anaerobiotic point (saturation at which deficient aeration occurs)	5	5
Canopy decline coefficient (% GDD^{-1})	0.709	0.15
Reference harvest index (%)	45	40
---Crop growth stages (GDD)---		
Time from sowing to emergence	80	200
Time from sowing to maximum green canopy cover	777	1522
Time from sowing to start senescence	853	2200
Time from sowing to maturity	1009	2700
Time from sowing to start flowering	536	1500
Length of the flowering stage	127	600

GDD = Growing Degree Day.

where
O_i= observed values in the field experiment for the ith observation;
$\bar{O}$ = average of the observed values;
P_i = model estimation values for the ith estimation;
$\bar{P}_i$ = average of the estimated values;
n = number of observations.

The RMSE ranges from 0 to + ∞, indicating ideal and poor performance, respectively. For agricultural models, a value of 15% is considered "good" and 20% is "satisfactory" (ADEBOYE et al., 2019). The mean bias error (MBE) indicates the percentage of the average deviation from the predicted values to the observed ones (ZACHARIAS et al., 1996). The EF, with values ranging from - ∞ to 1, indicates the distance between the observed and estimated data set on a 1:1 line. Models with performance values between 0 and 1 are generally considered acceptable. EF values lower than 0 indicate unacceptable performance (MORIASI et al., 2007). For studies of crop growth simulations, amounts of $r^2 > 0.80$ are recommended (MA et al., 2011).

RESULTS AND DISCUSSION

Figures 1a and 1b show a summary of the climatic data observed during experiments 1 and 2, respectively. During experiment 1, there were three rainfall events totalling 9.5 mm which took place shortly after sowing the crop and before the plant emerged. In experiment 2, there were 47 rainfall events, with the first event taking place 10 days after the emergence of the crop. Higher rainfall frequencies started 71 days after sowing, totalling 417.5 mm. In experiment 1, the ET_0 ranged from 1.7 to 7.4 mm d $^{-1}$, reaching its maximum value in August. In experiment 2, ET_0 amounts ranged from 1.9 to 7.1 mm d $^{-1}$. Average air temperature ranged from 16.9 to 23.2 °C in experiment 1 and from 20.4 to 28.1 °C in experiment 2. Solar radiation ranged from 6.4 to 20.8 MJ m $^{-2}$ d $^{-1}$ in experiment 1, with the highest amount in August. In experiment 2, solar radiation ranged from 6.7 to 27.0 MJ m $^{-2}$ d $^{-1}$, with its highest amount in December. Average hours of sunlight in experiment 2 were 9 h d $^{-1}$ and in experiment 1 average hours of sunlight were 7 h d $^{-1}$.

The canopy cover amounts obtained after model calibration (experiment 1) and validation (experiment 2), as well as model performance indicators for the different water deficit treatments, in different soybean growth stages, are shown in figure 2. Overall, calibration and validation results indicated good agreement between estimated and observed canopy cover data in all treatments, with high values of r^2 (> 0.84) and EF (> 0.84), low values of RMSE (ranging from 1.7 to 11.3%), and MBE (ranging from -3.3 to 7.1%). TIII and TIV treatments had the lowest precision for canopy cover estimation, in both calibration and validation experiments. After being calibrated, the model underestimated the maximum canopy coverage (at 70 DAS) by 3.8%, 1.2%, 0.4%, 4%, and 4.3% in the SE, TI, TII, TIII, and TIV treatments, respectively. In the validation, the model overestimated the maximum canopy cover (at 80 DAS) in 2.6%, 5.3%, 2.8%, and 2.4% in the SE, TI, TII, and TVI treatments, respectively, and underestimated it by 0.98% in the TIII treatment. Overall, after calibration, the model performed well in estimating canopy cover, having high EF and low RMSE. A good calibration of this parameter is essential for the model to correctly estimate biomass and crop yield since the canopy cover directly influences the transpiration rate and consequently the biomass accumulation (TERÁN-

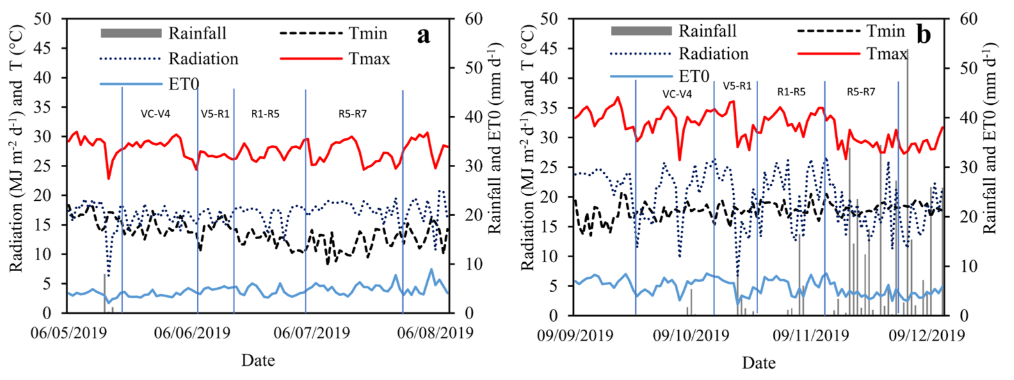
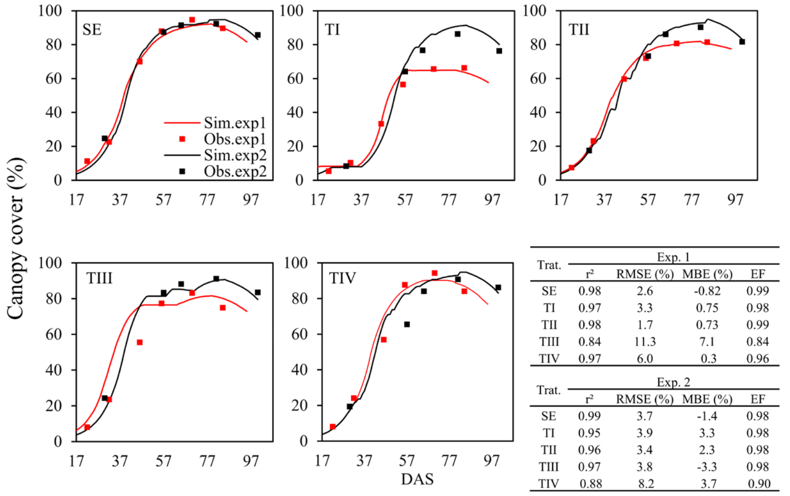


Figure 1 - Maximum (Tmax) and minimum (Tmin) air temperatures, solar radiation, rainfall, and reference evapotranspiration (ET0) in the experiments 1 (a) and 2 (b) during soybean cultivation.



Trat.	Exp. 1			
	r^2	RMSE (%)	MBE (%)	EF
SE	0.98	2.6	-0.82	0.99
TI	0.97	3.3	0.75	0.98
TII	0.98	1.7	0.73	0.99
TIII	0.84	11.3	7.1	0.84
TIV	0.97	6.0	0.3	0.96

Trat.	Exp. 2			
	r^2	RMSE (%)	MBE (%)	EF
SE	0.99	3.7	-1.4	0.98
TI	0.95	3.9	3.3	0.98
TII	0.96	3.4	2.3	0.98
TIII	0.97	3.8	-3.3	0.98
TIV	0.88	8.2	3.7	0.90

Figure 2 - The observed and estimated soybean canopy cover and performance indicators of the calibrated model for each treatment of experiments 1 and 2 (validation) as a function of days after sowing (DAS). SE = control treatment (without water deficit); TI = water deficit applied at the VC-V4 growth stage; TII = water deficit applied at the V5-R1 growth stage; TIII = water deficit applied at the R1-R5 growth stage; TIV = water deficit applied at the R5-R7 growth stage; Sim = estimated; Obs = observed; Exp = experiment.

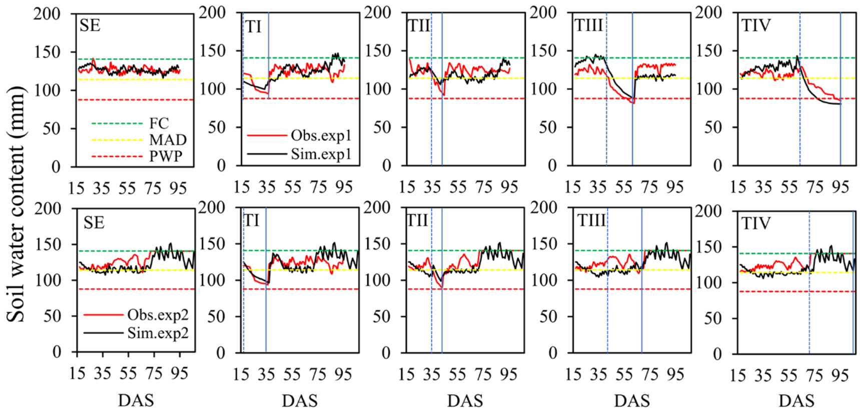
CHAVES et al., 2022; WELLENS et al., 2022). WANG et al. (2022) when analyzing the model for North China Plain conditions, they observed that the model slightly overestimates canopy cover during model calibration.

Soil water content values measured in experiment 1 and experiment 2 (validation), as well as the model performance indicators for the different treatments, are shown in figure 3. The performance indicators revealed that the soil water content simulation was not satisfactory. In experiment 1, the r^2 values ranged from 0.02 to 0.79, the RMSE ranged from 5.4 mm to 13.3 mm, which corresponds to 4.2% and 11.3% of the average soil water content of the SE and TIII treatments, respectively, the MBE ranged from -3.1 mm to 1.6 mm, the EF ranged from -0.8 to 0.26. In experiment 2, the r^2 amounts ranged from 0.40 to 0.58, RMSE ranged from 10.6 mm to 12.2 mm, which correspond to 8.4% and 9.4% of the average soil water content for the TI e TIV treatment, respectively, MBE ranged from -3.7 mm to -8.7 mm, and EF ranged from -0.65 to 0.54.

The model, after calibration, performed poorly in estimating soil water content, based on negative EF values, which were found for both experiments. The determination coefficient was relatively low for most of the treatments studied. These results indicated that the variability in soil water content was not well estimated by the model (ADEBOYE et al., 2019). Similarly, ZHAI et al. (2022) reported that AquaCrop tended to overestimate total soil water content, especially for treatments with irrigation deficit. However, it was noted that the model adequately estimated the water dynamic in the soil, satisfactorily representing the soil moisture behavior, especially during the water deficit phases. Other studies have shown results similar to the ones found in the present study (HUANG et al., 2022; AHMADI et al., 2022; SHAN et al., 2022).

The ETa values after model calibration (experiment 1) and validation (experiment 2), as well as the performance indicators for the different treatments under water deficit in different soybean growth stages, are shown in figure 4. Average daily evapotranspiration observed and estimated at each growth stage from the SE treatment from experiment 1 was equal to 0.9 mm d $^{-1}$ and 1.9 mm d $^{-1}$ (VC-V4), 1.2 mm d $^{-1}$ and 3.2 mm d $^{-1}$ (V5-R1), 2.7 mm d $^{-1}$ and 3.2 mm d $^{-1}$ (R1-R5), 2.5 mm d $^{-1}$ and 3.5 mm d $^{-1}$ (R5-R7). Observed and estimated average daily evapotranspiration during the period under water deficit in the TI, TII, TIII, and TIV treatments from experiment 1 were equal to 0.30 mm d $^{-1}$ and 0.61 mm d $^{-1}$, 0.8 mm d $^{-1}$ and 2.7 mm d $^{-1}$, 1.0 mm d $^{-1}$ and 2.7 mm d $^{-1}$, 1.3 mm d $^{-1}$ and 0.78 mm d $^{-1}$, respectively.

In experiment 2, average daily evapotranspiration amounts observed and estimated at



Treat.	Exp. 1			
	r^2	RMSE (mm)	MBE (mm)	EF
SE	0.02	5.4	0.31	-0.8
TI	0.25	11.6	0.93	-0.15
TII	0.05	10.8	-3.1	-0.47
TIII	0.43	13.3	1.6	0.33
TIV	0.79	10.7	0.3	0.26

Treat.	Exp. 2			
	r^2	RMSE (mm)	MBE (mm)	EF
SE	0.44	11.3	-7.8	-0.3
TI	0.58	10.6	-3.7	0.54
TII	0.51	11.3	-5.8	0.34
TIII	0.42	11.8	-7.6	-0.25
TIV	0.40	12.2	-8.7	-0.65

Figure 3 - Observed and estimated values of daily soil water content in the 0-0.4m layer and performance indicators of the calibrated model for each treatment of experiments 1 and 2 (validated) as a function of days after sowing (DAS). SE = control treatment (without water deficit); TI = water deficit applied at the VC-V4 growth stage; TII = water deficit applied at the V5-R1 growth stage; TIII = water deficit applied at the R1-R5 growth stage; TIV = water deficit applied at the R5-R7 growth stage; Sim = estimated; Obs = observed; Exp = experiment. FC – field capacity; PWP – permanent wilting point; MAD – management allowed depletion. The vertical blue lines represent the beginning (dashed) and the end (continuous) of the water deficit application according to crop growth stages.

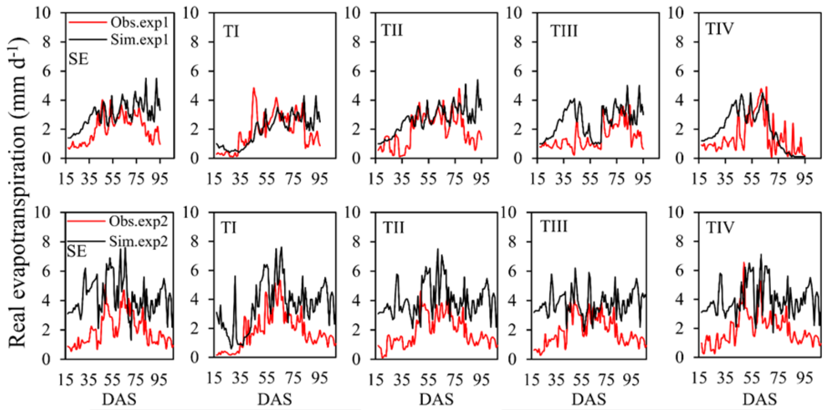
each crop growth stage from the SE treatment were equal to 1.0 mm d $^{-1}$ and 3.9 mm d $^{-1}$ (VC-V4), 1.8 mm d $^{-1}$ and 4.9 mm d $^{-1}$ (V5-R1), 3.0 mm d $^{-1}$ and 4.8 mm d $^{-1}$ (R1-R5), 2.0 mm d $^{-1}$ and 3.9 mm d $^{-1}$ (R5-R7). Treatments TI, TII, TIII, and TIV observed and estimated average daily values of ETa in the period under water deficits equal to 0.30 mm d $^{-1}$ and 1.9 mm d $^{-1}$, 1.0 mm d $^{-1}$ and 3.3 mm d $^{-1}$, 3.0 mm d $^{-1}$ and 3.3 mm d $^{-1}$, 1.8 mm d $^{-1}$ and 3.7 mm d $^{-1}$, respectively.

The model performance in estimating the soybean ETa sown in experiments 1 and 2 was not satisfactory. In experiment 1, r^2 ranged from 0.11 to 0.29, RMSE ranged from 1.0 to 1.6 mm d $^{-1}$, which corresponds to 54% and 112% of the average ETa of the TI and TIII treatments, MBE ranged from 0.07 mm d^{-1} to 1.1 mm d $^{-1}$, EF ranged from -2.5 to 0.25. In experiment 2, r^2 ranged from 0.04 to 0.21, RMSE ranged from 2.3 mm d $^{-1}$ to 2.7 mm d $^{-1,}$ which corresponds to 128% and 137% of the average ETa of the TI e SE treatments, respectively, MBE ranged from de 1.8 mm d $^{-1}$ to 2.3 mm d $^{-1}$, and EF ranged from -5.3 to -2.3.

One of the reasons for the model's bad performance in estimating ETa is the model's poor performance in estimating soil water content (SANDHU & IRMAK, 2019). The accurate estimation of soil water content is an indicator of good ETa estimation of the soil water balance component from the AquaCrop model (ALVAR-BELTRÁN et al., 2023). In the present study, irrigation took place through a buried drip irrigation system, in which the Es amount tends to be zero. Additional studies are needed to assess the model's performance for this type of irrigation system, especially regarding ETa estimations.

In experiment 1, the absolute error in estimating total ETa in the cycle ranged from +5.9 to +91.2 mm. In experiment 2, errors ranged from +159.3 to +208.3 mm. In experiment 1, such an error would be equivalent to 91200 m³ of water, considering an irrigated area of 100 ha. In experiment 2, the highest absolute error was found in the SE treatment with a difference between observed and estimated volumes of 208300 m³ for a cultivated area of 100 ha. The magnitude of the numbers highlights the importance of an adequate ETa estimation.

The biomass values assessed in experiment 1 and experiment 2, as well as the model performance

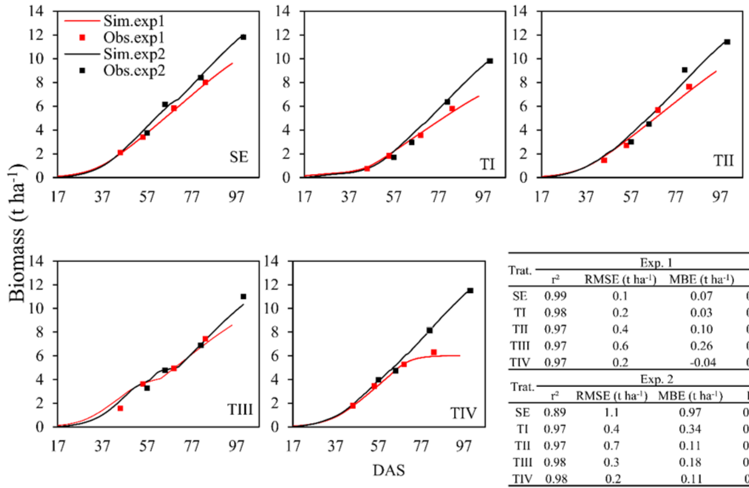


Treat.	Exp. 1			
	r^2	RMSE ($mm\ d^{-1}$)	MBE ($mm\ d^{-1}$)	EF
SE	0.23	1.3	1.0	-1.0
TI	0.29	1.0	0.07	0.25
TII	0.19	1.3	0.80	-0.44
TIII	0.11	1.6	1.1	-2.5
TIV	0.25	1.4	0.5	-0.28

Treat.	Exp. 2			
	r^2	RMSE ($mm\ d^{-1}$)	MBE ($mm\ d^{-1}$)	EF
SE	0.05	2.7	2.3	-5.3
TI	0.21	2.3	1.8	-2.3
TII	0.08	2.5	2.2	-4.8
TIII	0.07	2.3	1.8	-4.5
TIV	0.04	2.5	2.2	-4.3

Figure 4 - Observed and estimated values of daily real evapotranspiration and performance indicators of the calibrated model for each treatment of experiment 1 and 2 (validation) as a function of days after sowing (DAS). SE = control treatment (without water deficit); TI = water deficit applied at the VC-V4 growth stage; TII = water deficit applied at the V5-R1 growth stage; TIII = water deficit applied at the R1-R5 growth stage; TIV = water deficit applied at the R5-R7 growth stage; Sim = estimated; Obs = observed; Exp = experiment.

indicators for the different treatments under water deficit in different soybean growth stages are shown in figure 5. Overall, the model performed well in estimating the aboveground dry biomass for all treatments in both experiments. In experiment 1, the r^2 ranged from 0.97 to 0.99, RMSE ranged from 0.1 t ha^{-1} to 0.6 t ha^{-1}, which corresponds to 2% and 13.7% of the average biomass of SE and TIII treatments, MBE



Trat.	Exp. 1			
	r^2	RMSE ($t\ ha^{-1}$)	MBE ($t\ ha^{-1}$)	EF
SE	0.99	0.1	0.07	0.99
TI	0.98	0.2	0.03	0.99
TII	0.97	0.4	0.10	0.97
TIII	0.97	0.6	0.26	0.93
TIV	0.97	0.2	-0.04	0.98

Trat.	Exp. 2			
	r^2	RMSE ($t\ ha^{-1}$)	MBE ($t\ ha^{-1}$)	EF
SE	0.89	1.1	0.97	0.88
TI	0.97	0.4	0.34	0.98
TII	0.97	0.7	0.11	0.96
TIII	0.98	0.3	0.18	0.98
TIV	0.98	0.2	0.11	0.99

Figure 5 - Observed and estimated soybean aboveground dry biomass and performance indicators of the calibrated model for each treatment in experiment 1 and 2 (validation) as a function of days after sowing (DAS). SE = control treatment (without water deficit); TI = water deficit applied at the VC-V4 growth stage; TII = water deficit applied at the V5-R1 growth stage; TIII = water deficit applied at the R1-R5 growth stage; TIV = water deficit applied at the R5-R7 growth stage; Sim = estimated; Obs = observed; Exp = experiment.

ranged from -0.04 MBE t ha $^{-1}$ 0.26 t ha $^{-1}$, EF ranged from 0.93 to 0.99. In experiment 2, the r^2 ranged from 0.89 to 0.98, RMSE range from 0.2 t ha $^{-1}$ to 1.1 t ha $^{-1}$, which corresponds to 2.8% and 16.5% of average biomass from the TVI and SE, respectively, MBE ranged from 0.11 t ha $^{-1}$ to 0.97 t ha $^{-1}$, EF ranged from 0.88 to 0.99. The model performed well in estimating biomass for all treatments (Figure 5), which is related to a good estimation of canopy cover (Figure 2). AquaCrop's good performance in estimating biomass was also noted by other authors (IZADI et al., 2023; AZIZ et al., 2022; ADEBOYE et al., 2019). Despite the model's poor performance in estimating ETa, it performed well in estimating biomass. This may be related to the calibration with normalized water productivity (WP) because the model uses WP as a parameter for estimating biomass.

Yield amounts were higher in experiment 2, compared to experiment 1 (Table 2). This difference can be attributed to climatic conditions, mainly the number of hours of light and the maximum air temperature, which have a great influence on the growth of the soybean crop. In addition, the cultivar used in this study has indeterminate growth, which allows changes in its physiological characteristics mainly due to the climatic conditions to which it is subjected. In experiment 2, the rains became more frequent after 70 DAS, and for this reason the TI treatment (water deficit applied at the VC-V4 growth stage) was impacted by the applied water deficit, showing that in the absence of rain in this stage the plant reduces its yield by approximately 30% when compared to the SE treatment (Table 2).

The yield amounts obtained after the model calibration (experiment 1) and validation (experiment 2) for the different treatments are shown in table 2, and the correlation between observed and estimated yield for each treatment in experiments 1 and 2 is shown in figure 6. The model estimated, with good performance, the soybean crop yield for all the treatments in both experiments. In experiment 1, the r^2 was 0.98, RMSE = 0.06 t ha $^{-1}$, and EF equal to 0.98. In experiment 2, r^2, RMSE, and EF were equal to 0.99, 0.06 t ha $^{-1}$, and 0.99, respectively. The model performed well in estimating soybean crop yield in both experiments (Figure 6). Although it rained during the model's validation period, the was still able to adequately (error = 0.2 t ha $^{-1}$) estimate the final yield in each treatment. The differences reported in the soybean yield in the same treatment in both experiments are due to differences in sowing dates and climatic conditions. MORALES-SANTOS et al. (2023) also noted AquaCrop's good performance in estimating soybean yield under water deficit conditions. MBANGIWA et al. (2019) noted AquaCrop's good soybean crop yield estimation.

CONCLUSION

The AquaCrop model performed well in estimating the soybean's canopy cover evolution under water deficits applied at different growth stages. Although, the model overestimated the soil water content, it was able to adequately estimate the soil water dynamic. The model's ETa estimation was

Table 2 - The observed and estimated yield for each treatment in experiments 1 and 2.

	Treatment	--------------------------------Yield (t ha^{-1})------------------------------	
		Observed	Estimated
Experiment 1	SE	3.2	3.2
	TI	2.3	2.2
	TII	2.8	2.8
	TIII	2.2	2.3
	TIV	2.0	2.0
Experiment 2	SE	5.6	5.5
	TI	4.0	4.0
	TII	4.9	4.9
	TIII	4.9	5.0
	TIV	5.2	5.2

SE = control treatment (without water deficit); TI = water deficit applied at the VC-V4 growth stage; TII = water deficit applied at the V5-R1 growth stage; TIII = water deficit applied at the R1-R5 growth stage; TIV = water deficit applied at the R5-R7 growth stage.

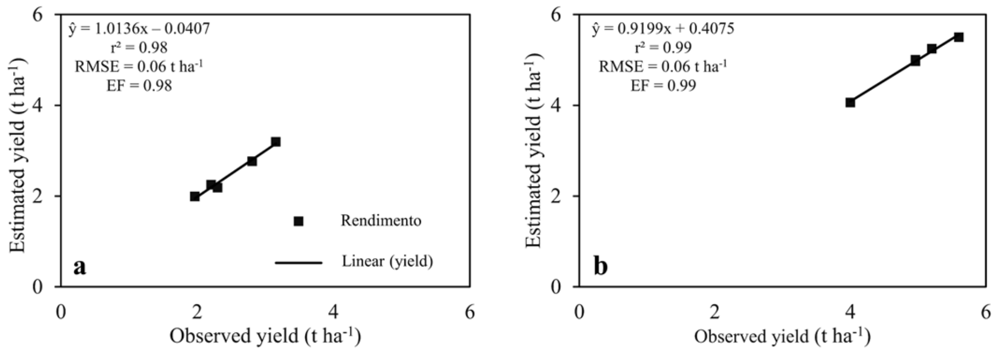


Figure 6 - Correlation between observed and estimated yield data of the calibrated model for each treatment in experiment 1 (a) and 2 (b).

not satisfactory for all treatments, which is noted by the low correlation between observed and estimated values and low estimation efficiency. The model performed well in estimating biomass and soybean crop yield.

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DECLARATION OF CONFLICT OF INTEREST

The authors declare no conflict of interest. The founding sponsors had no role in the design of the study; in the collection, analyses, or interpretation of data; in the writing of the manuscript, and in the decision to publish the results.

AUTHORS' CONTRIBUTIONS

All authors contributed equally for the conception and writing of the manuscript. All authors critically revised the manuscript and approved of the final version.

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