Agrociencia Uruguay 2023 | Volume 27 | Number NE1 | Article e1185
DOI: 10.31285/AGRO.27.1185
ISSN 2730-5066

Advances in Water in Agroscience

Adjustment of the AquaCrop model in maize with different levels of irrigation in southern Uruguay temperate climate conditions

Ajuste del modelo AquaCrop en maíz con diferentes niveles de riego en condiciones de clima templado del sur de Uruguay

Ajuste do modelo AquaCrop em milho com diferentes níveis de irrigação em condições de clima temperado no sul do Uruguai

Hayashi, R.[1]; Dogliotti, S.[2]

[1]*Universidad de la República, Facultad de Agronomía, Departamento de Suelos y Aguas, Montevideo, Uruguay*
[2]*Universidad de la República, Facultad de Agronomía, Departamento de Producción Vegetal, Montevideo, Uruguay*

Editor

Álvaro Otero
Instituto Nacional de Investigación Agropecuaria (INIA), Salto, Uruguay

Received *28 Abr 2023*
Accepted *03 Oct 2023*
Published *06 Feb 2024*

Correspondence

Raquel Hayashi
rhayashi@fagro.edu.uy

Abstract

The AquaCrop model allows evaluating and designing irrigation strategies that improve the use of irrigation water. The objective of this research was to calibrate and validate the AquaCrop model for maize to the climatic conditions of southern Uruguay, with different irrigation water management. This model was calibrated and validated for corn using experimental data from irrigation trials with different deficit levels in three seasons, 2015-16 and 2016-17 (calibration) and 2014-15 (validation). Three maximum irrigation depths were evaluated: 3, 6 and 9 mm day^{-1}, and rainfed (rainfall only). The crop was parameterized for local conditions and water stress coefficients were adjusted. The calibration simulated the yield, biomass and soil moisture in the irrigated treatments with good performance. All the statistic indexes used to evaluate the adjustment between the observed and simulated data model indicated a good model performance, with the exception of the efficiency coefficient of the Nash-Sutcliffe (EF) model. The model underestimated the yield in the rainfed treatment (EF of -0.52) when root depth was limited to 0.7 m. However, the test soil allowed for greater radical exploration than the initially used. At 0.90 m root depth, the model was good at simulating the yields in the rainfed treatment, mainly in dry years (EF of 0.79). The model predicts the yield with good adjustment in different irrigation and rainfall situations if the stress coefficients are adjusted and the crop is properly parameterized, mainly the root depth.

Keywords: deficit irrigation, crop simulation, *Zeamays*, humid climate

Resumen

El modelo AquaCrop permite evaluar y diseñar estrategias de riego que mejoren el uso del agua de riego. El objetivo del presente trabajo fue ajustar el modelo AquaCrop para el cultivo de maíz a las condiciones climáticas del sur de Uruguay, con diferentes manejos del agua de riego. Se calibró y validó este modelo para maíz utilizando datos experimentales de ensayos de riego con diferentes niveles deficitarios, en tres temporadas: 2015-16 y 2016-17 (calibración) y 2014-15 (validación). Se evaluaron tres láminas máximas de reposición: 3, 6 y 9 mm día-1, y secano (solo precipitaciones). El cultivo fue parametrizado para las condiciones locales y se ajustaron los coeficientes de estrés hídrico. La calibración simuló bien el rendimiento, la biomasa y la humedad del suelo en los tratamientos regados. Todos los índices estadísticos utilizados para evaluar el modelo indicaron un buen ajuste entre datos observados y simulados, a excepción del coeficiente de eficiencia del modelo de Nash-Sutcliffe (EF). En el secano, el modelo subestimó el rendimiento

(EF de -0,52), cuando la profundidad radical se limitó a 0,7 m. Sin embargo el suelo del ensayo permitía una mayor exploración radical que la utilizada inicialmente. Con 0,90 m de profundidad, el modelo simuló bien el rendimiento del secano, principalmente en el año seco (EF de 0,79). El modelo predice el rendimiento con buen ajuste en diferentes situaciones de riego y precipitaciones si se ajustan los coeficientes de estrés y el cultivo es parametrizado en forma adecuada, principalmente la profundidad de raíces.

Palabras clave: riego deficitario, simulación cultivos, *Zea mays*, clima húmedo

Resumo

O modelo AquaCrop permite avaliar e desenhar estratégias de irrigação que melhoram o uso da água de irrigação. O objetivo deste trabalho foi ajustar o modelo AquaCrop para cultivo de milho às condições climáticas do sul do Uruguai, com diferentes manejos de água de irrigação. Este modelo foi calibrado e validado para milho utilizando dados experimentais de ensaios de irrigação com diferentes níveis de déficit, em três safras, 2015-16 e 2016-17 (calibração) e 2014-15 (validação). Foram avaliados três níveis máximos de reposição: 3, 6 e 9 mm dia-1, e terra seca (apenas precipitação). A cultura foi parametrizada para as condições locais e os coeficientes de estresse hídrico foram ajustados. A calibração simulou bem a produtividade, a biomassa e a umidade do solo nos tratamentos irrigados. Todos os índices estatísticos utilizados para avaliar o modelo indicaram um bom ajuste entre os dados observados e simulados, exceto o coeficiente de eficiência do modelo Nash-Sutcliffe (EF). Na terra seca, o modelo subestimou o desempenho (FE de -0,52), quando a profundidade das raízes foi limitada a 0,7m. No entanto, o solo de teste permitiu uma exploração mais radical do que a utilizada inicialmente. Com profundidade de 0,90 m, o modelo simulou bem o desempenho do sequeiro, principalmente no ano seco (EF de 0,79). O modelo prevê a produtividade com bom ajuste em diferentes situações de irrigação e precipitação se os coeficientes de estresse forem ajustados e a cultura for parametrizada adequadamente, principalmente a profundidade das raízes.

Palavras-chave: irrigação deficitária, simulação colheita, Zea mays, clima úmido

1. Introduction

Current population growth projections estimate that by 2030 there will be around 8.5 billion people[1]. This growing population will increase the demand for food, fiber, and water-related services. Competition for water use across various activities, partly intensified by population growth, puts pressure on food production. In temperate and humid zones, climate change will cause disruptions in precipitation patterns and intensity, making them less effective for crops and increasing runoff[2]. Maximizing the efficiency of water and energy use stands as a primary goal in many research projects to achieve greater productivity of water and other production resources. This not only improves the use of scarce resources, but also the profitability and sustainability of production.

Maize is a primary summer crop in Uruguay and holds global economic importance, used for human and animal consumption, energy production, and various industrial products. However, it's predominantly grown under rainfed conditions, and yields vary significantly between years[3], depending on summer rainfall.

In Uruguay, the occurrence of maximum cumulative precipitation deficit events during spring and summer does not show significant generalized trends, although in most weather stations the trend is towards decreasing deficits. This is not incompatible, however, with the existence of historically high deficit events (associated with extreme droughts) in recent years. In 2015, water deficits notably impacted the agricultural sector, resulting in significant economic losses[4].

On the other hand, the availability of irrigation water does not present significant limitations[5]. However, irrigation is used in a low percentage of the area planted with summer crops (3%), except for rice, which is entirely cultivated under irrigation. One of the primary arguments preventing wider adoption of irrigation, particularly in maize, are the high energy costs[6]. Nevertheless, deficit irrigation strategies are alternatives that improve water use efficiency[7] and reduce direct irrigation costs.

A strategy worth considering is planning the use of water stored in the soil to meet crop water needs during the period of highest demand. Implementing this strategy requires the irrigation system to operate in a way that ensures that the available soil water reservoir is full before entering the peak period. The water requirements during this stage can be met through the irrigation system and planned depletion of the root zone. The extent to which the design flow rate for the irrigation system is reduced depends on the available water (stored in the root zone) and the length of the peak period. This strategy carries the risk that an abnormally long period of maximum usage or system failures during or before the maximum usage period could cause unplanned crop stress due to water shortage[8-9].

These deficit irrigation alternatives should be evaluated to encompass diverse environmental conditions (climate and soil) that typically occur in temperate and humid climates. Experimentally, it is possible to gather information limited to the experimentation period. The use of crop simulation models aids in evaluating irrigation and crop management strategies, provided the model is appropriately calibrated and validated for the study area.

The AquaCrop model, developed by the FAO[10-11] and used worldwide for assessing crop response to water, is considered a decision-making tool for defining crop management strategies that mitigate the consequences of climate change. In Uruguay, the model has been parameterized for maize using water-deficit experiments, showing a good fit in situations of comfortable water conditions or moderate deficit, while in situations of severe water deficit the simulation was inadequate[12]. Under these severe conditions, the model estimated lower yields due to underestimation of transpiration and total biomass produced.

This study aims to adjust the AquaCrop model for maize cultivation to the climatic conditions in southern Uruguay, considering various irrigation water management.

2. Material and methods

2.1 Field experiments

The necessary data to fit the AquaCrop model corresponds to field data collected during three seasons of maize experiments with deficit irrigation[13]. These experiments were conducted at the Experimental Field of the Agronomy College, Southern Regional Center, Canelones, Uruguay (34°37’ S and 56°13’ W) during 2014-15, 2015-16, and 2016-17 seasons. According to the Koppen and Geiger classification, the climate is temperate/mesothermal with no dry season and a hot summer (Cfa). The average annual precipitation stands at 1200 mm with high interannual variability and yearly irregularity.The average summer temperature ranges between 18 and 23 °C, with average radiation levels varying between 16.75 and 24.27 MJ m-2 day^{-1}, and an average humidity of 72%.

The dominant soil type is a typic Eutric Brunisol Lac., from the Tala Rodríguez Soil Unit, corresponding to a typic Argiudoll according to the USDA taxonomic classification. Information about its hydraulic properties is presented in Table 1. The methodology described by García-Petillo and others[14] was used to determine these properties.

Table 1. Soil characteristics used in the model corresponding to the experiment soil

Horizon (m	Saturation Vol %	FC Vol %	PWP Vol %	BD grcm^{-3}	Ksat mm day^{-1}	Texture
0 - 20	52.0	38.9	22.5	1.25	500	Fr Lm Ac
20 - 40	46.0	43.6	25.1	1.43	300	Fr Ac
40- 60	46.0	38.6	21.4	1.43	200	Fr Ac
+ 60	47.6	38.4	21.4	1.40	200	Fr Ac
Curve Number:		72				
Rapidly evaporable water from surface horizon (mm): 13						

FC: field capability; PWP, permanent wilting point; BD, bulk density; Ksat: hydraulic conductivity in saturated flow; Vol %: Volumetric humidity

The soil infiltration rate is 8.8 mm h^{-1}, measured using the double-ring infiltrometer method when the soil moisture content was at 50% of the available water depletion (irrigation threshold).

2.2 Experimental design

The corn trials consisted of three irrigation treatments and a non-irrigated control: 3 mm (maximum daily replacement depth of 3 mm day^{-1}), 6 mm (maximum daily replacement depth of 6 mm day^{-1}), 9 mm (maximum daily replacement depth of 9 mm day^{-1}), and rainfed (only receives precipitation). Each treatment indicates the maximum daily replenishment capacity with irrigation. If the crop's daily water requirements exceed these depths, irrigation will be deficient, generating different levels of deficit irrigation in different phenological stages of the crop.

The experimental design constituted complete randomized blocks with four treatments and four replications. The plots were 12×6 m, with 12 rows separated by 0.50 m, with no free spaces between plots to avoid edge effects that might generate different microclimatic conditions within the trial (oasis effect). The total experimental area was 1152 m^2.

2.3 Crop management

Maize hybrids with high productive potential were used[15]. The planting dates were November 6, 2014, October 30, 2015, and November 9, 2016. Direct seeding was performed, with rows 0.50 m apart and 0.15 m between plants, aiming for a target population of 100,000 plants ha^{-1}. Pre and post-seeding herbicide applications were carried out to prevent weed emergence. To avoid nutritional restrictions, 78 kg ha^{-1} of N and 200 kg ha^{-1} of P_2O_5 (Diammonium Phosphate, 18-46-0) were applied at sowing, and 150 kg ha^{-1} of N (Urea) was reapplied at V6.

For precise irrigation depths, a drip irrigation system with pressure limiters was used for each treatment to achieve high uniformity in each plot. One lateral per crop row was installed, with 4 l h^{-1} drippers every 1.0 m in a staggered configuration for better water distribution. The application rate was 8 mm h^{-1}, matching the soil's infiltration rate. Irrigations were performed two or three times per week, applying the water corresponding to the total need of the previous days, up to the maximum allowed in each treatment.

2.4 Data collection and measurements

2.4.1 Meteorological data

Meteorological data required for climate files in the model were obtained from the weather station at the National Institute of Agricultural Research (INIA), Las Brujas, located 20 km from the study site. The climate characterization of the three seasons and the rainfall, locally obtained during the experimental period, are detailed in Hayashi and Dogliotti[13].

2.4.2 Crop measurements

Crop phenology was determined through plant observation and using the Ritchie and Hanway scale[16]. The evolution of above ground biomass and crop growth rate (CGR) was evaluated in the second and third years of the trial. Approximately every 30 days, plants from a one-meter linear section in the central part of each plot were extracted and dried in an oven at 60 ºC to constant weight. Crop coverage was measured using a ceptometer (Accupar LP-80, METER Group). Grain yield was determined by manually harvesting three subsamples of 2 m^2 each from the central rows of each plot (6 m^2 per plot). Grain yield, total dry matter, and weight of 1000 grains were measured, and grain weight was adjusted to 14% moisture content. Finally, the harvest index (HI) was estimated as dry grain weight/total dry matter.

2.4.3 Soil moisture evolution

Soil moisture was monitored using a neutron probe (CPN, model 503-DR Hydroprobe, Campbell Pacific Nuclear Corp., CA, USA) in the first two years, and with a portable capacitance probe (FDR, Delta T Devices, PR2) in the last year. Both probes were calibrated for each horizon up to a depth of 100 cm. Measurements with the probes were performed two to three times a week, and in the case of the FDR probe, before and after irrigation. Measurements were performed in all treatments, in two replications.

2.5 Parameterization, calibration and validation of the AquaCrop model

The AquaCrop model estimates crop yield based on biomass estimation. It is a simple, robust, and user-friendly model[10-17]. Yield estimation is done in four stages. The first simulates crop cover (CC). Based on the crop cover, in the second stage the model estimates transpiration (T), considering the different stresses that can occur throughout the crop cycle. In the third stage, transpiration is used to calculate biomass (B), taking into account normalized water productivity (WP*). Finally, B is used to estimate the final crop yield[10-17].

2.5.1 Model parameterization and calibration

The AquaCrop model requires crop data to perform simulations based on the water consumed. Maize crop has a default calibration in this model[10-11]; however, some parameters must be adjusted for the local conditions where the experimentation was conducted.

For model calibration, the experimental data from the 2015-16 season were considered due to the agrometeorological conditions, which determined a higher water demand associated with higher yields. Field evaluations were more intensive during that season. Data from the 9 mm treatment, developed under comfortable water conditions, were used as it expressed the highest achievable yield and biomass without water deficiencies. Subsequently, other deficit irrigation treatments were run to adjust stress parameters. Crop cover, biomass, yield, and soil water content were compared.

The evaluation of the AquaCrop model at different crop water levels was achieved by comparing the simulated canopy development, biomass accumulation, grain yield, and soil moisture with the observed field data.

2.5.2 Other considerations

The trial was conducted without nutritional deficiencies, in the absence of weeds, and with good-quality irrigation water, so these aspects were not considered in the model adjustment. The experimental site has a slight slope (1%), and the cultivation followed this slope to favor runoff from abundant rainfall. To prevent waterlogging that might harm the crop, this field management option was selected in the model.

Simulations began 10 days before the planting date, allowing the incorporation of pre-planting rainfall into the water balance, which affected the simulated soil moisture data by AquaCrop. For each treatment and season, a soil water content file was compiled using data measured with a neutron probe or FDR in the field experiment, and in the last two seasons, aboveground biomass production files (OBS) were created. The model then performed statistical analysis of the fit of the simulations (SIM) with the observed data (OBS).

2.5.3 Procedure for model adjustment

Non-conservative model parameters were first adjusted: planting density, initial and final root depth, time at which the maximum root depth was reached, maximum coverage, and duration of different phenological stages. Subsequently, the adjustment of other model parameters was iterative, primarily modifying non-conservative parameters. Simulations were run for each change in input data using the calibrated crop file and the corresponding irrigation file for each treatment. Once a good fit of the model parameters was achieved for the non-water-deficit treatment, simulated values and measured biomass and grain yield were compared for deficit irrigation treatments.

2.5.4 Statistical evaluation of model fit

To assess the goodness of fit of biomass and soil moisture simulation by AquaCrop, the model uses the following statistical indices: Pearson correlation coefficient (r), root mean square error (RMSE in mm), normalized root mean square error (NRMSE %), Nash-Sutcliffe model efficiency coefficient (EF)[18], and Willmott's agreement index (d) (Eq. 1 to 5).

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

r, Pearson’s correlation coefficient, can take values between 0<r<1. A higher r value indicates a better fit. This goodness-of-fit measure is recommended when a linear relationship is expected between the observed and simulated variables.

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

RMSE, the root mean square error, expresses the variance of the residual error, ranging from 0 to +∞. It indicates how well the measured value fits with the predicted value from the model. When it is close to 0, it indicates a good fit between the measured and simulated values.

$$NRSME= \frac{RSME}{\bar{O}} \quad (3)$$

NRMSE, the ratio between RMSE and the mean of the observed values, expressed as a percentage. Simulation is excellent when NRSME is less than 10%, good between 10 and 20%, acceptable between 20 and 30%, and poor if it's greater than 30%[19].

$$EF=1-\frac{\sum_{i=1}^{n}(S_i-O_i)^2}{\sum_{i=1}^{n}(O_i-\bar{O})^2} \quad (4)$$

EF, the Nash-Sutcliffe efficiency coefficient, expresses the relative magnitude of the root mean square error when compared to the variance of the observed data. It ranges between -∞ and 1, where EF = 1 indicates a perfect fit, EF = 0 suggests that the model's predictions are as precise as the average of the measured data, and if negative, it indicates that the average of the measured data provides a better prediction than the model, i.e., that the model does not contribute.

Table 2. Nash-Sutcliffe Efficiency Indicators (EF)

EF	Adjustment
< 0.2	Insufficient
0,2-0,4	Satisfactory
0,4-0,6	Well
0,6-0,8	Very good
> 0.8	Excellent

Source: Nash & Sutcliffe[18]

$$d=1-\frac{\sum_{i=1}^{n}(S_i-O_i)^2}{\sum_{i=1}^{n}(|S_i-\bar{O}|+|O_i-\bar{O}|)^2} \quad (5)$$

Where: O_i: Observed value (measured); $\bar{O}$: ; average of the observed values; S_i: simulated value; $\bar{S}$: average of the simulated values.

d, Willmott's concordance index[20], varies between 0 and 1. There is a good fit when d is close to 1, and a bad fit if it is close to 0.

For the grain yield variable, the coefficient of determination (R^2), the regression coefficient (b) and the mean absolute error (MAE) were added.

$$R^2 = \left\{ \frac{\sum_{i=1}^{n}(O_i-\bar{O})(S_i-\bar{S})}{\left[\sum_{i=1}^{n}(O_i-\bar{O})^2\right]^{0.5}\left[\sum_{i=1}^{n}(S_i-\bar{S})^2\right]^{0.5}} \right\}^2 \qquad (6)$$

R^2, coefficient of determination, ranges from 0 to 1, values greater than 0.5 are considered acceptable[21], and the closer to 1, the lower the variance error.

$$b = \frac{\sum_{i=1}^{n}(O_i \times S_i)}{\sum_{i=1}^{n} O_i^2} \qquad (7)$$

b, regression coefficient; close to 1, it indicates that the simulated values are statistically close to the observed.

$$\text{MAE} = \frac{1}{n}\sum_{i=1}^{n}|O_i - S_i| \qquad (8)$$

MAE, mean absolute error, expresses the magnitude of the mean of the estimation errors. It quantifies the accuracy of a prediction technique by comparing predicted versus observed values.

$$\text{Pe}\ (\%) = \frac{(S_i - O)}{O_i} \times 100 \qquad (9)$$

Pe, error prediction, expresses the percentage by which the simulated value differs from the observed value. The lower the value (positive or negative) indicates the better model fit.

3. Results and discussion

3.1 Adjusting the AquaCrop Model

Table 3 outlines the key adjusted parameters used in AquaCrop to simulate maize biomass and grain yield.

The Harvest Index (HI) used in the model (55%) was higher than the 48% calibrated in the default model[21] owing to the high-yield maize genotypes recommended in the cultivar assessment conducted by INASE-INIA.

The root depth was iteratively parametrized. It started at a 0.70 m depth, which rendered satisfactory yields and biomass under irrigated treatments. However, the rainfed treatment did not achieve a good fit. Depths of 0.80, 0.90, and 1.00 m were evaluated, and at 0.90 m simulations for rainfed treatments matched observed data better (see Table 4).

The time from sowing to maximum root depth was adjusted. Default parameters indicate that maximum depth is reached when the crop enters the senescence stage[22]. According to Tarjuelo[23], in annual crops, maximum effective root depth is attained when maximum Kc is reached and remains constant until the end of the crop cycle. Other studies[24] suggest root growth up to phenological stage R3, after which it is limited. They also indicate that this stage occurs approximately 80 days after emergence. In calibration, this stage was placed at the onset of flowering (71 days post-sowing). This adjustment impacted the simulations as yields achieved in the trials were not simulated since the model assumed less available water during the yield formation stage, due to reduced root exploration. By modifying this, yields aligned better with observed data. Steduto and others[21] indicate a root growth rate in maize from 2.0 to 2.3 cm day^{-1}, implying that maximum depth (2.30 m) is reached at the beginning of senescence. This study considers that roots might reach 0.90 m or 1.0 m, these depths occurring 10 days after the crop reaches maximum coverage.

The planting density of 100,000 plants per hectare (trial data) altered the initial crop coverage (CC_o) to 90% emergence, amounting to 65% concerning the 70,000 plants per hectare calibration (46%). Although the individual plant canopy size (cc_o) is a conservative parameter, planting density affects CC_o, defined as the multiplication of cc_o by the plant density[25]. This parameter influences water losses due to evaporation in the initial stage, which is unproductive for the crop (evaporated water not used by the plant). As the crop attains greater ground cover in less time (more shading), these losses decrease, improving water usage.

The growth and decrease parameters for crop canopy (CGC and CDC) were calibrated at 13.37% day^{-1} and 12.53% day^{-1}, respectively. These values differ by 18 and 7% from the proposed values[21]. Calibrated CGC is lower, implying the crop has a slower canopy growth rate and reaches maximum coverage later; conversely, CDC is higher, indicating a shorter period to senescence. However, the adjusted model presents an extended flowering and yield-building phase compared to default values, which can impact the final crop yield. The WP* (34.3 g m-2) was similar to that proposed by

Hsiao and others[21] and that obtained by other researchers[26-27].

Water stress coefficients are related to water depletion in the root zone. The stress-inducing stomatal closure (stomatal conductance, Ks_{sto}), according to the FAO calibration[21], begins when soil moisture falls below 0.69 of TAW (water stress-tolerant crops). This coefficient was adjusted to 0.45 (crops sensitive to water stress). Other studies adjusted it to 0.5 of TAW (moderately sensitive to sensitive to water stress)[26][28-29]. Adjusting this coefficient is critical as it indicates the moisture level at which stomatal closure processes begin, associated with potential yield reduction by influencing the transpiration rate[25]. In local experiments using the default Ks_{sto}[21], errors occurred in maize under low rainfall years, attributing these errors to the non-adjustment of the stress coefficients[12], reinforcing the need to adjust these values.

Table 3. AquaCrop default conservative and non-conservative parameters[21] and adjusted values used in maize simulation

Conservative parameters	**Model**	**Calibrated**
Normalized crop water productivity (g m $^{-2}$)	33.7	34.3
Reference Harvest Index (%)	48	55
Base temperature (°C)	8	8
Maximum temperature (°C)	30	30
Canopy Growth Coefficient (%/day) CGC	16.312	14.789
Canopy Decline Coefficient (%/day) CDC	11.691	13.724
Increase in cover (in fraction of land cover/GDD, Growing Degree Day)	0.0125	0.0118
Decrease in cover (in fraction of covered land, in GDD)	0.010	0.00954
Crop transpiration coefficient at 100% coverage	1.05	1.12
Soil Water Depletion Factor for Canopy Expansion (Upper Threshold)	0.14	0.10
Soil Water Depletion Factor for Canopy Expansion (Lower Threshold)	0.72	0.60
Soil Water Depletion Factor for Stomatal Control (Upper Threshold)	0.69	0.45
Non-conservative parameters	**Model**	**Calibrated**
Plant density (pl ha^{-1})	70000	100000
Initial crop coverage at 90% emergence (%)	46	65
Maximum Crop Cover (CCx) in Fraction of Soil Cover	0.96	0.96
Time from Seed to Emergence, GDD	80	65
Time from Sowing to Maximum Root Depth, GDD (days)	1409	927
Time from Sowing to Onset of Senescence, GDD	1400	1422
Time from Sowing to Flowering, GDD	880	886
Time From Sowing to Maturity, GDD	1700	1724
Flowering Stage Length, GDD	180	232
Harvest Index Build Duration, GDD	750	827
Minimum Effective Root Depth (m)	0.30	0,.0
Maximum rooting depth (m)	2.30	0.70
Maximum extraction of water by the roots in the first quarter of the root zone (m^3 of water m^{-3} of soil. day)	0.045	0.048
Maximum water extraction by the roots in the last quarter of depth (m^3 of water m^{-3} of soil day)	0.011	0.007

3.2 Model adjustment: calibration and validation

3.2.1 Grain yield and aboveground biomass production

Table 4 presents the observed (OBS) corn grain yield data compared to AquaCrop-simulated yields (SIM). The 2015-16 and 2016-17 season data were used for model calibration, while the 2014-15 data were used for validation.

Prediction error (Pe) from AquaCrop model calibration and validation displayed high absolute values for the rainfed treatment (78.2% and 31.8%) in the seasons when ETo exceeded the 38-year average for the study area[13]. In these years, the model simulated lower yields compared to experimental observations. For the other treatments, Pe (%) was below 10%. All model fit indicators used to evaluate the calibration (NRMSE, RMSE, d, R2, MAE, b) show good fit, except for EF, which yielded negative values, indicating that the model does not contribute. However, these indicators, including EF, improved when simulating root depth adjustments for the rainfed treatment (see Tables 4, 5, 6, and 7).

The final simulated biomass production exhibits a strong fit with observed field experiment results, considering the adjustment indicators detailed in Tables 6 and 7 and the previously mentioned ranges for each indicator. For Pe, the rainfed treatment in the 2015-16 season presented the highest absolute value (30.6%), as was the case with the grain yield in this treatment.

Rainfed treatments exhibited the highest error in model predictions during low rainfall years (2014-15 and 2015-16). Similar findings were obtained locally for yields and biomass production in treatments with water deficiencies during flowering (critical period)[12]. In years with limited rainfall, AquaCrop underestimated yield and biomass. Giménez[12] attributed the estimation errors to a mismatch of stress coefficients (Ks) for severe water deficiency conditions. Another potential cause is associated with the growth and effective root system depth. The maximum root depth in rainfed crops can be greater, reaching 1.70 m in soils without root exploration impediments[30-31]. The trial's soil characteristics could allow exploration down to 0.90-1.00 m; however, initial simulations were performed with an effective root depth of 0.70 m. Subsequently, simulations with greater depth were considered: 0.80 to 1.0 m for the rainfed treatment. With 0.90 m, the model simulated rainfed yields with lower errors, both in yield and biomass (Tables 5 and 7).

The provided data include simulated values considering a depth of 0.90 m for the rainfed treatment. Model fit indicators significantly improve, especially the coefficient of efficiency (EF), shifting from negative to positive values over 0.50, indicating a good fit. Consequently, the analysis will continue to consider the rainfed simulation with a root depth of 0.90 m.

Table 4. Maize yield (t ha^{-1}), simulated (SIM) and observed (OBS) in calibration and validation of the AquaCrop model, error prediction (Pe). Rainfed values were simulated with a root depth of 70 and 90 cm

PERFORMANCE (t ha^{-1})					
2015-16 (Calibration)					
	OBS	SIM			
		0.70 m	Rainfed with 0.90 m	Pe (%) 0.70 m	Pe (%) 0.90 m
Rainfed	9.323	2.028	7.833	**-78.2**	**-16.0**
3 mm	12.917	13.309		3.0	
6 mm	14.247	15.377		7.9	
9 mm	14.665	16.013		9.2	
2016-17 (Calibration)					
Rainfed	13.364	12.847	14.222	-3.9	64
3 mm	14.818	15.312			-3.3
6 mm	16.103	15.756			-2.2
9 mm	17.108	15.861			-7.3
2014-15 (Validation)					
Rainfed	12.786	8.720	10.868	**-31.8**	**-15.0**
3 mm	13.616	13.815		1.5	
6 mm	15.379	15.070		-2.0	
9 mm	17.466	16.009		-8.3	

Table 5. Statistical indices of model fit for the variable grain yield. Nash-Sutcliffe model (EF) efficiency coefficient, normalized root mean square error (NRMSE), Willmott concordance index (d), coefficient of determination (R^2), mean absolute error (MAE at tha^{-1}), root mean square error (RMSE at t ha^{-1}), and regression coefficient (b)

	Calibration		Validation		
	0.70 m	Rainfed with 0.90 m	0.70 m	Rainfed with 0.90 m	Units
EF	-0.52	0.79	-0.46	0.54	
NRMSE	19.1	7.2	14.6	8.2	%
d	0.83	0.95	0.78	0.89	
R^2	0.82	0.85	0.70	0.81	
MAE	1.596	0.91	1.51	0.97	t ha^{-1}
RMSE	2.708	1.01	2.17	1.22	t ha^{-1}
b	0.97	1.01	0.91	0.94	

The greater root depth increases the exploration area and reduces the moisture deficit (moisture depletion) if the deeper soil layers retain high water content[26]. During the 2015-16 season trails, scant rainfall events occurring before and during the crop cycle allowed the soil profile to recharge down to 0.90 m, allowing the crop to use water stored at that depth when rainfall was limited (barely 11 mm) during the critical period (January 2016). Consequently, rainfed yield was minimally affected, yielding 9.323 t ha^{-1}[13].

Table 6. Total Observed Biomass (OBS) and Simulated Biomass (SIM) with the AquaCrop Model, error prediction (Pe)

BIOMASS (t ha^{-1})

		OBS	SIM		Pe (%)	
			0.70 m	Rainfed with 0.90 m	0.70 m	Rainfed with 0.90 m
2015-16	Rainfed	18.169	12.614	15.624	-30.6	-14.0
	3 mm	28.854	24.527		-15.0	
	6 mm	31.355	28.529		-9.0	
	9 mm	33.722	29.734		-11.8	
2016-17	Rainfed	26.683	23.810	26.361	-10.8	-1.2
	3 mm	28.766	28.377		-1.4	
	6 mm	30.767	29.240		-5.0	
	9 mm	30.731	29.435		-4.2	

Table 7. Statistical indices of model fit for biomass. Coefficient of determination (R^2), root mean square error (RMSE at t ha^{-1}), normalized root mean square error (NRMSE %), efficiency coefficient of the Nash-Sutcliffe model (EF), Willmott concordance index (d), mean absolute error (MAE), and regression coefficient (b)

Index	Rainfed with 0.70 m	Rainfed with 0.90 m	Units
R^2	0.93	0.90	
RMSE	3.28	2.58	t ha^{-1}
NRMSE	11.4	9.00	%
EF	0.45	0.66	
d	0.90	0.92	
MAE	2.85	2.15	t ha^{-1}
b	0.91	0.93	

3.2.2 Soil water content

Figure 1 presents the evolution of the total soil water content simulated by the model and observed in the field experiment for the most water-deficient treatments (rainfed and 3 mm irrigation). For the rainfed treatment, total water was considered to a depth of 0.90 m with a total water content at FC of 357 mm, a PWP of 202 mm, and a TAW of 155 mm.

Table 8 shows the model's fit indicators between simulated and observed total soil water content for the four treatments and the three evaluation years provided by AquaCrop. Overall, good fits were achieved in all treatments.

The model fit indicators for the variable total water evolution in the root depth show a good fit between OBS and SIM values (Table 8, Figures 1 and 2). The model's efficiency coefficient (EF) ranged from 0.45 to 0.92, indicating a good to excellent fit according to Molnar's classification(18). In the 2016-15 season, the RMSE was 20.0 and 15.8 mm, and the EF was 0.50 and 0.45 in the rainfed and 3-mm treatments, respectively. While the fit is good, these were the two situations where the simulations showed less agreement with the observed values.

In the 6 and 9 mm irrigation treatments, the soil water content was close to field capacity (FC), and at times even above FC. These situations, which were more frequent in the 9 mm treatment, were due to the irrigation management with low thresholds (near FC) and the occurrence of rainfall after irrigation. This irrigation management, allowing daily consumption to exhaust and replenish the generated deficit, typical of high-frequency irrigation methods (drip irrigation and center pivot), is safe for meeting crop water needs, especially in critical stages, where water demands are higher, and irrigation thresholds are more demanding compared to early or late stages(8)(23)(30). However, they are inefficient in using rainfall and can generate situations where soil moisture content exceeds FC, as observed in the trial, mainly in the 2016-17 season. In poor draining soil conditions, water logging issues may arise, but this was not the case in this trial.

The results indicate that AquaCrop effectively simulates yields under mild water stress and proper irrigation (3, 6, and 9 mm) throughout the three evaluated seasons, each with different climatic situations (medium PP, low PP and abundant PP)(13). However, the rainfed treatment was influenced by the climatic conditions of each evaluated season and by the root depth of the crop. In situations with high atmospheric demand (ETo) and scarce rainfall, the rainfed treatment had a better fit in yield and biomass when a root depth of 0.90 m was considered. In a year with abundant rainfall, the fit was good with both 0.70 and 0.90 m.

It is necessary to consider that the tested conditions were carried out in soil typical of the southern region of Uruguay (Typic Argiudolls) with a medium to high available water retention capacity(32), which is a crucial soil water parameter for irrigation management and crop response.

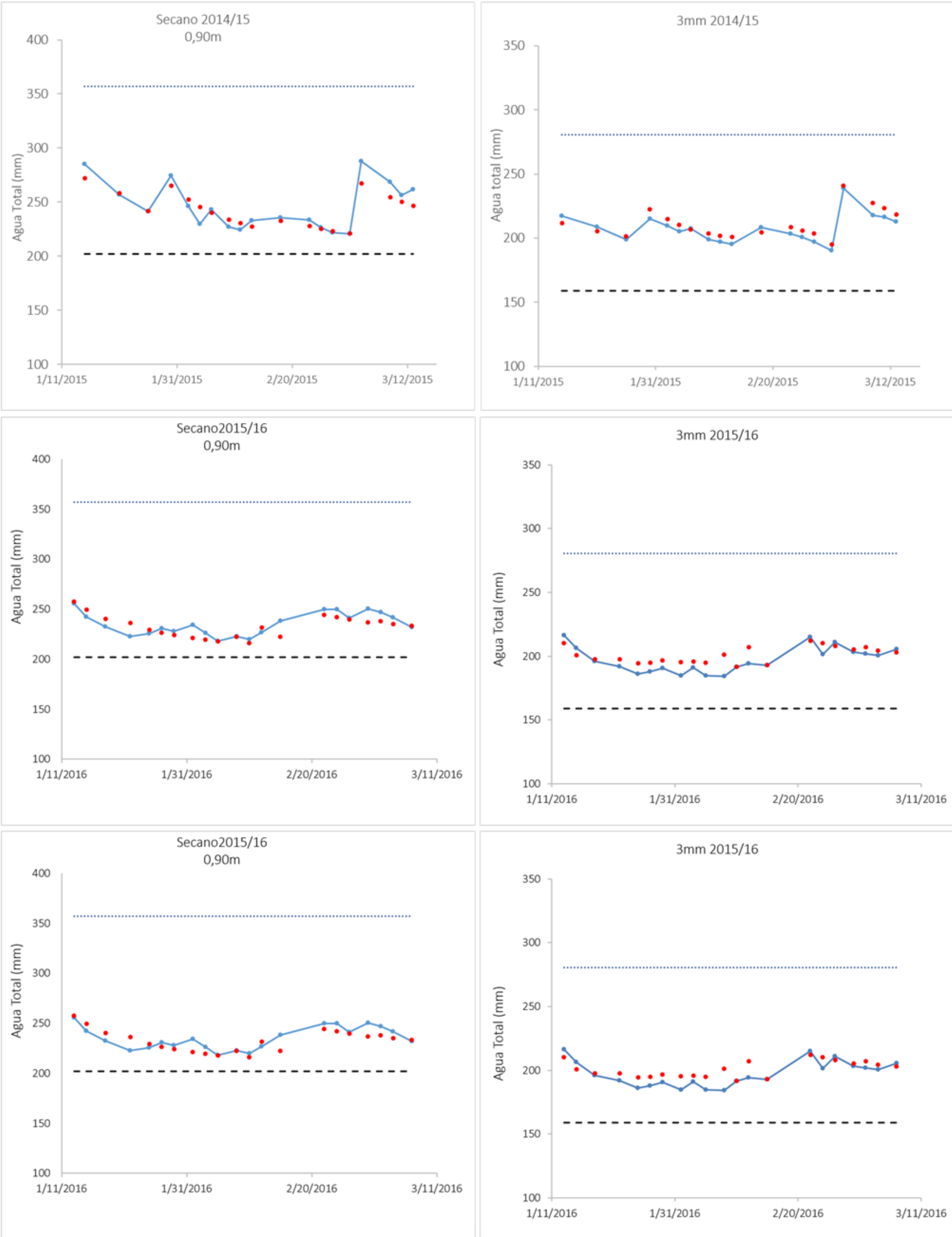

Figure 1. Evolution of total water (mm), simulated (red dots) and observed (blue line), at 0.90 m root depth in rainfed treatment and at 0.70 m in 3 mm treatment. Total water content (mm) at field capacity (....... FC), and on the verge of permanent wilting (- - - - - PWP)

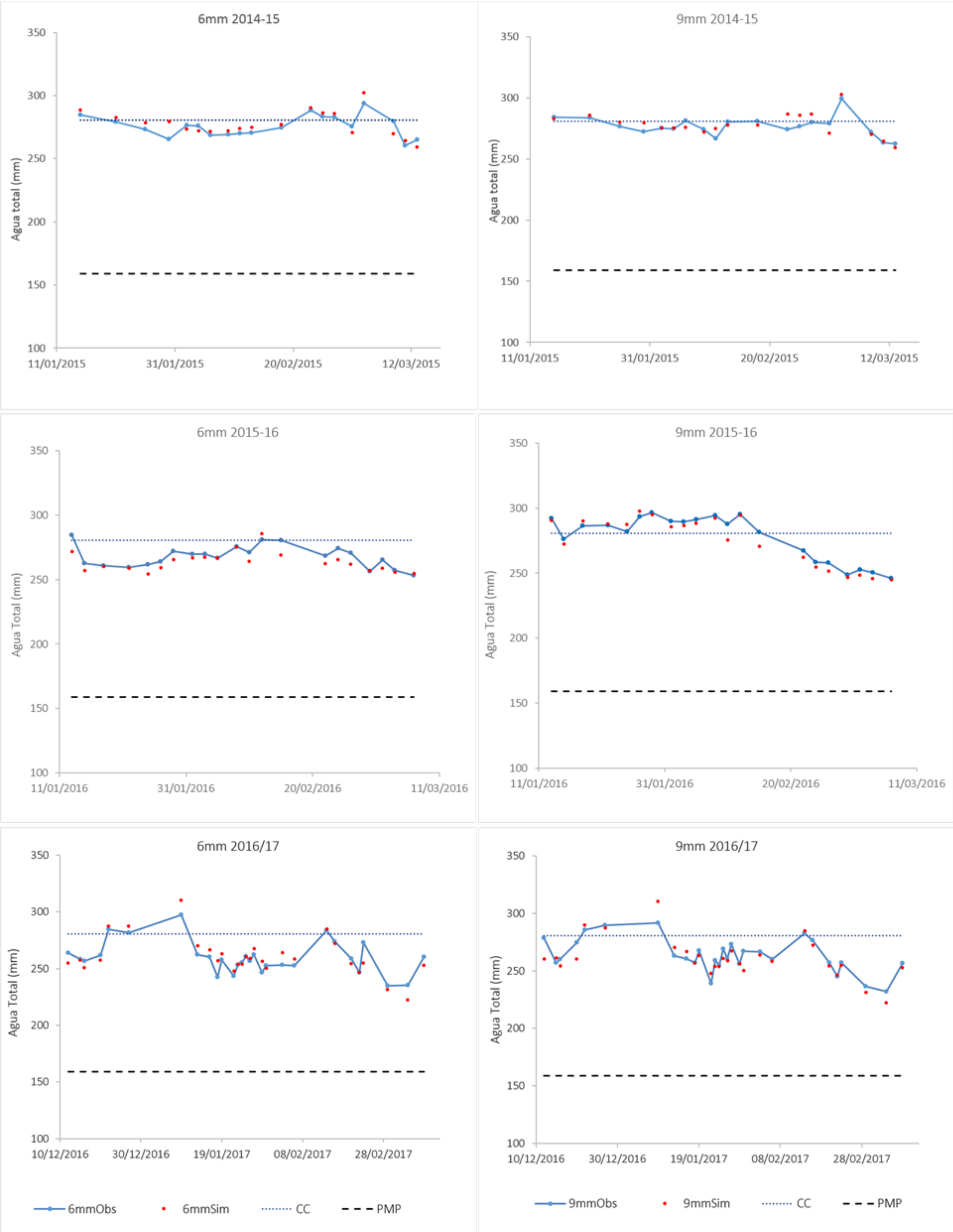

Figure 2. Evolution of total water (mm), simulated (red dots) and observed (blue line), at 0.70 m of root depth, in the 6 mm and 9 mm treatments. Total water content (mm) at field capacity (....... FC), and on the verge of permanent wilting (- - - - - PWP)

Table 8. Model fit indicators between simulated and observed values of total soil water content for the 4 treatments and the 3 years of evaluation estimated by the model

	Treatments	r	RMSE (mm)	NRMSE (%)	EF	Wilmott Index (d)
2014/15	Rainfed	0.93	9.2	3.7	0.81	0.93
	3 mm	0.93	5.3	2.5	0.76	0.94
	6 mm	0.84	5.6	2.0	0.55	0.90
	9 mm	0.83	5.4	2.0	0.54	0.90
2015/16	Rainfed	0.78	7.6	3.3	0.53	0.87
	3 mm	0.80	7.1	3.6	0.45	0.80
	6 mm	0.84	6.1	2.3	0.45	0.85
	9 mm	0.97	5.0	1.8	0.92	0.98
2016/17	Rainfed	0.82	20.0	6.7	0.50	0.89
	3 mm	0.75	15.8	6.5	0.45	0.83
	6 mm	0.90	7.4	2.8	0.73	0.94
	9 mm	0.90	7.7	2.9	0.71	0.94

r, Pearson's correlation coefficient; RMSE, root mean square error; NRMSE, normalized root mean square error; EF, efficiency coefficient of the Nash-Sutcliffe model; d, Willmott's concordance index.

4. Conclusions

a. The AquaCrop model adequately simulated the yield and biomass production of the irrigation treatments (3, 6, and 9 mm) and the rainfed treatment when the rooting depth was set at 0.90 m.

b. The AquaCrop model simulated very well the evolution of soil water content in both the irrigated and rainfed treatments.

c. The results of this study suggest that AquaCrop could be used in our country to assess deficit irrigation strategies in maize.

d. To achieve a good fit, it is necessary to adjust the crop stress coefficients to enhance the simulation quality.

e. This study confirms that the simplicity of the AquaCrop model, requiring minimal input data, readily available, makes it user-friendly for professional or research end-users when evaluating deficit or full irrigation strategies.

f. AquaCrop is a valuable tool that would allow the evaluation of irrigation options with greater productivity of pumped water and better use of rainfall, thus helping to mitigate the effects of climate change on irrigated crops.

Acknowledgements

The study was funded by the FSA_1_2013_1_12590 project from ANII (National Agency for Research and Innovation).

Transparency of data

Available data: The entire data set that supports the results of this study was published in the article itself.

Author contribution statement

RH: experiment design, writing, analysis of results, statistical processing, interpretation of results. SD: contribution in writing and in the interpretation of results.

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