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CROP SCIENCE

Evaluation of models to estimate the actual evapotranspiration of soybean crop subjected to different water deficit conditions

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Abstract: Optimization of water use for irrigation will only be possible with the adjustment of management, which is directly related to the correct estimate of the actual evapotranspiration of the crop. The present study aimed to evaluate different mathematical approaches used in estimating the actual evapotranspiration of a new soybean cultivar (BRS 7581RR) subjected to different water deficit conditions. For this, the ETa estimated by the FAO56 Dual, Jensen and Hermann, AquaCrop and Ritchie models was evaluated. The experimental design was randomized with five treatments and four replicates. Irrigation management in the treatments was conducted so as to maintain different levels of water available in the soil (AW). The T1 treatment was performed applying 80 to 100% AW; in T2 treatment, the allowed variation was 60 to 80% AW; in T3 treatment, it was 40 to 60% AW; in T4, from 20 to 40% AW; and in T5, from 0 to 20% AW. The results showed that the FAO56 Dual model showed better performance in soybean ETa estimation for winter conditions in most treatments, with NSE ranging from 0.42 to 0.83. In the summer, the Jensen and Hermann model showed the best results, with NSE ranging from 0.70 to 0.94.

Key words: Cerrado, modeling, irrigation management, water resources.

INTRODUCTION

Brazil plays an important role in the global food production, standing out as a producer and exporter of various agricultural commodities, especially soybean crop. More than half of the area cultivated with soybean in Brazil (35.7 Mha), in the 2018/19 season, was concentrated in the Cerrado biome (Agrosatélite 2020). The Cerrado, the second largest biome in extension and main agricultural frontier, is a strategic region for maintaining the hydrological balance in Brazil.

Although it is a crop typically cultivated under rainfed conditions, soybean has been increasingly cultivated in irrigated systems, which has contributed to increasing water demand in the Cerrado region, an area that already faces water problems in some of its main watersheds. About 64% of the irrigated area in Brazil is located in this region (BRASIL 2014), which concentrates approximately 80% of all center pivots (Althoff & Rodrigues 2019).

In the Cerrado region, the long periods of droughts recently observed, together with the rapid economic development of the region, and the lack of monitoring of hydroclimatic variables and adequate management of water resources have contributed to the occurrence of water scarcity. In this context, it is important to develop strategies to reduce the amount of water removed from the springs by the various uses, which can be made possible through an integrated watershed planning that establishes effective strategies to increase the efficiency of the various uses, especially irrigation, which is the main user.

Any strategy that aims to improve irrigation efficiency should prioritize the adjustment of management. In the literature, it is possible to find the description of several methods (Allen et al. 1998, Doorenbos & Pruitt 1977, Torres et al. 2019) and instruments (Contreras et al. 2017, Gonçalves et al. 2019, Qi et al. 2020, Zheng et al. 2020) that can be used to manage an irrigation system. Mathematical models considering the characteristics of climate, soil and plant (Chibarabada et al. 2020, Er-Raki et al. 2010, Jensen & Heermann 1970, Paredes et al. 2015, Rodrigues et al. 2005) to define when and how much to irrigate are, in general, the easiest option for operation in the field.

Among the existing models, the one proposed by Doorenbos & Pruitt (1977), which calculates the potential evapotranspiration of the crop (ETc) through the relationship between the evapotranspiration of a reference crop (ETo) and a crop coefficient (Kc), has been the most used due to its simplicity and ease of programming and operationalization. ETo represents atmospheric demand, differing between localities. Kc varies according to the crop and to its stage of development (Allen et al. 1998).

For the calculation of the actual crop evapotranspiration (ETa), based on the procedures that use Kc, the most usual method is to correct the value of ETc according to a crop water stress coefficient (Ks), which is a function of soil moisture, and a coefficient that considers soil evaporation (Ke), which is a function of vegetation cover and the frequency of soil wetting (Allen et al. 2006, Jensen & Heermann 1970, Pereira et al. 2013).

Other approaches with great potential for application are those based on methodologies that estimate ETa through the individualized calculation of transpiration and direct evaporation of soil water (Ea), such as the model of Jensen and Heermann (Jensen & Heermann 1970), the model of Ritchie (1972), FAO56 Dual and AquaCrop (Hsiao et al. 2009, Raes et al. 2009, Steduto et al. 2009). These approaches are also useful in the management of watersheds, as they make it possible to investigate the magnitude of Ea, which is considered a loss of water not beneficial to the system, that is, this water does not contribute effectively to production.

The Jensen and Heermann model, as well as FAO56 Dual, calculate ETa based on Ks, Ke and a basal crop coefficient (Kcb). In the AquaCrop model, transpiration is calculated as a function of vegetation cover and ETo, while in the Ritchie model transpiration is calculated as a function of leaf area index and maximum crop evapotranspiration. For the last two models, evaporation is calculated considering the two phases of water evaporation in the soil.

Several authors have studied the behavior of these models in the estimation of ETa in several regions of the world. Rodrigues et al. (2005, 1997), studying the model of Ritchie (1972), were successful in estimating ETa for barley and bean crops, respectively. Alves et al. (2020) obtained good results using the model of Jensen & Heermann (1970) to evaluate the impact of climate and plant conditions on the irrigated depth for maize crop. AquaCrop also showed good results in the estimation of ETa for soybean (Mbangiwa et al. 2019) and barley (Pereira et al. 2015). The FAO56 Dual model, used by Jiang et al. (2019) and Paredes et al. (2018), also showed good performance in Eta estimation.

Although these methodologies for ETa estimation are well known and have already been applied in various regions of the world

(Bello & Walker 2017, Rodrigues et al. 1997, Tan et al. 2018), little has been done for the conditions of the Brazilian Cerrado region and even less for the new soybean varieties that are launched annually in the Brazilian market.

The Cerrado region faces serious water problems in some of its main watersheds, and it is necessary to develop technical coefficients of irrigation for the new varieties and improve irrigation management, through better estimates of ETa. Thus, the present study aimed to evaluate the performance of different mathematical approaches to estimate the actual evapotranspiration of a new soybean cultivar (BRS 7581RR) subjected to different water deficit conditions.

MATERIALS AND METHODS

Study area

To determine the variables and parameters necessary to calculate ETa by the different models, two experiments were installed (winter and summer of 2019), with the soybean cultivar BRS 7581RR (indeterminate growth type), at the Reference Unit in Water Management (*Unidade de Referência em Manejo de Água* - URMA), located in the Agricultural Research Center of the Cerrados (Embrapa Cerrados). With an elevation of 979 m, URMA is located in the Central Plateau region of the Cerrado Biome (15°35’55.1”S, 47°42’27.4”W).

The climate of the region is classified as Aw (Köppen 1948) with average air temperature of 22 °C and rainfall of 1,500 mm year^{-1}, concentrated between October and March (Malaquias et al. 2010). The soil of the area is classified as *Latossolo Vermelho* (Oxisol), containing 52% clay.

Irrigation was performed using a micro-sprinkler irrigation system. The system consisted of 16-mm-diameter tubes connected to a 32-mm-diameter mainline, both made of polyethylene. The micro-sprinklers were spaced by 3.0 m between rows and 5.0 m from one another, with operating pressure of 20 mwc, flow rate of 87 L h^{-1} and precipitation intensity of 5.3 mm h^{-1}.

Experimental design

The experiments were set up in a randomized block design, with four replicates (4 m x 2 m) in each of the five treatments (9 m x 20 m), totaling twenty experimental plots.

In each treatment, an irrigation strategy was applied based on water available in the soil (AW). The T1 treatment was performed applying 80 to 100% AW; in T2 treatment, the allowed variation was 60 to 80% AW; in T3 treatment, it was 40 to 60% AW; in T4, from 20 to 40% AW; and in T5, from 0 to 20% AW.

Irrigation management and soil moisture measurement

The irrigation depth applied in each treatment was calculated based on the actual soil moisture value, using the equation

$$LA = \frac{10(\theta_{UL} - \theta_{actual[T1,T2,T3,T4\ or\ T5]})}{Ef} Z \quad (1)$$

where: LA = irrigation depth applied, mm; θ_{UL} - soil moisture at the upper limit of treatment, m^3 m^{-3}; θ_{actual} = actual soil moisture in each treatment (TI, T2, T3, T4 or T5), m^3 m^{-3}; Z = depth of the root system of the crop, cm; and Ef = Efficiency of irrigation system (Ef = 0.85).

Irrigation was applied when soil moisture measured in the root zone of the crop reached the pre-established value range in each experimental unit. Soil moisture was determined using the gravimetric method. Soil samples were collected daily in the 0-20 and 20-40 cm layers in each experimental plot, weighed and subsequently dried in an oven at 105 °C for 24 h. After drying, the soil samples were weighed again. After obtaining the wet and dry weights, the actual soil moisture was obtained and the irrigation depth to be applied in each treatment was calculated.

Root system depth was evaluated weekly in all treatments for the winter and summer experiments. For this, three plants were randomly collected in the area of each experimental unit and evaluated for maximum root length. To enable the daily management of irrigation, the sigmoidal model with three parameters was fitted to the observed data.

Other data collected

The climatic data needed to run the models were obtained from the weather station of Embrapa Cerrados, located approximately 2 km away from the experiment. Temperature, relative humidity, wind speed, solar radiation and precipitation data were used.

Due to its variability, precipitation was measured by two rain gauges installed in the experimental area. Reference evapotranspiration was calculated by the FAO-Penman Monteith equation (Allen et al. 1998).

Eighteen soil samples were collected to evaluate soil texture, soil water retention curve and apparent density at depths of 0-20 and 20-40 cm. Texture was estimated using the procedure defined by Teixeira et al. (2017). The retention curve was constructed using the methodology of the tension table (Leamer & Shaw 1941, Oliveira 1968) for the points of 1, 3, 6, 10, 33, 60 kPa and Richards' pressure plate apparatus (Richards 1947) for 800 and 1500 kPa. For the apparent density, the volumetric ring method was used (Teixeira et al. 2017).

The leaf area index (LAI) was calculated by the ratio between leaf area per plant and planting density. To estimate the leaf area of the plant, eight plants per treatment were collected at a frequency of ten days. After collection, the plants were placed in plastic bags and taken to the Plant Biology Laboratory of Embrapa Cerrados, where their leaves were separated and leaf area was calculated using an electronic planimeter (LI-3100C). LAI was calculated for all treatments for the winter and summer experiments. To enable the daily modeling of ETa, the Gaussian Peak model with three parameters was fitted to the observed data.

Crop management

Based on the result of the chemical analysis of the soil of the experimental area, fertilization was performed for soybean crop, by applying in the sowing furrow 22.5 kg of N, 112.5 kg of P_2O_5 and 112.5 kg of K_2O per hectare, as recommended by Sousa & Lobato (2004).

Sowing was performed on May 6 (winter) and September 9 (summer) of 2019 with the cultivar BRS 7581RR, using 18 plants per linear meter and spacing of 0.5 m between rows, aiming at a population of 360,000 plants ha^{-1}. Harvests were carried out on August 9 (winter) and December 25 (summer) of 2019, respectively.

After sowing, irrigation depths were applied in order to keep the soil moist and thus ensure the germination and emergence of seedlings. The conventional sprinkling system was used up to 10 days after sowing (DAS).) At 12 DAS, the plants received the first depth of the micro-sprinkler system. From 13 DAS, monitoring was initiated for the application of each strategy, which ended at 90 DAS, in the winter experiment, and at 107 DAS, in the summer experiment.

During the experiment, the necessary phytosanitary treatments were carried out, with applications of herbicide, fungicide and insecticide.

Estimated actual evapotranspiration

Actual evapotranspiration was calculated based on soil moisture variation estimated by the gravimetric method (ETa_{GRA}) and estimated by the models FAO56 Dual (ETa_{DUAL}), Jensen and Heermann (ETa_{JEN}), AquaCrop (ETa_{ACRP}) and Ritchie (ETa_{RIT}).

ETa_{GRA} was calculated using the equations

$$ETa_{0-40cm} = 10\left\{ \left[\left(\theta_{1i0\text{-}20cm} - \theta_{2i0\text{-}20cm}\right) Di\right] + \left[\left(\theta_{1i\ 20\text{-}40cm} - \theta_{2i\ 20\text{-}40cm}\right) Di\right]\right\}, \ for\ 0 \le Z \le 40 \quad (2)$$

where: θ_{1i} = volumetric moisture on day i, $m^3\ m^{-3}$; θ_{2i} = volumetric moisture on day i-1, $m^3\ m^{-3}$; Di = layer thickness, cm (20 cm). For Z ≤ 20, B = 0.

The ETa_{DUAL} and ETa_{JEN} models are more accurate in showing the effects of daily variations in humidity on the soil surface and the resulting impacts on ETa on the soil water profile. This is the case for high-frequency irrigation with micro-irrigation systems or lateral movement systems, such as center pivots and linear movement systems. ETa_{DUAL} and ETa_{JEN} were calculated according to the procedures described by Allen et al. (1998) and Jensen & Heermann (1970), respectively, according to the equation

$$ETa = ETo\ (Ks\ Kcb + Ke) \quad (3)$$

For both models, plant transpiration is calculated through a basal crop coefficient and a coefficient to represent the water stress of the crop. Soil evaporation is represented by an evaporation coefficient. For Kcb values, the procedures described in FAO56 were used for the winter and summer experiments. The difference between the models lies in the calculation of Ks and Ke. While ETa_{DUAL} adopts a linear behavior, calculated according to the amount of water stored in the soil, for the reduction of Ks, ETa_{JEN} uses a logarithmic model. In the case of Ke, ETa_{DUAL} considers the two phases of drying and the soil cover by the crop, while ETa_{JEN} uses the following Ke values for the first, second and third days after a rainfall event or irrigation, respectively: (0.9 – Kcb) 0.8; (0.9 – Kcb) 0.5; (0.9 – Kcb) 0.3.

ETa_{RIT} was developed to calculate the ET of crops planted in a row where the water supply in the soil is not limited, and the crop is not at an advanced stage of maturation or senescence. ETa_{RIT} was calculated according to procedures described by Ritchie (1972), Ritchie & Johnson (1990) and Jones & Ritchie (1990). In its basic formulation, Ritchie model calculates the direct evaporation of water in soil separated from T, which was calculated as a function of maximum evapotranspiration (ET_{MAX}) and LAI.

In the calculation of Es, the first two phases of direct evaporation of soil water described by Philip (1957) are considered. The first phase is characterized by a relatively high evaporation, controlled by atmospheric conditions. The second phase starts from the moment the Es rate is not sufficient to meet the atmospheric demand. The parameter U corresponds to the amount of water that evaporates in phase 1, while α is a constant equivalent to the diffusivity of water on the soil surface during phase 2 of drying. The value of U represents the change from phase 1 to phase 2 of evaporation of water from the soil, and its value is obtained in the inflection of the curve plotted on the graph of accumulated evaporation (ΣEs) as a function of the day after irrigation. The value of α consists of the slope of the line originating from the linear regression between the accumulated evaporation data (ΣEs) in phase 2 and the square root of time, in days.

To estimate the values of the parameters U and α, eight weighing micro-lysimeters with internal diameter of 150 mm were installed in the experimental area and kept for a period of twenty-five days. The management of micro-lysimeters, as well as the estimation of U and α, followed the procedures described by Rodrigues et al. (2005).

ETa_{ACRP} aims to simulate the response of crop yields to water availability, and furthermore to determine ET. The model can perform well, using a relatively small number of parameters. ETa_{ACRP} was calculated according to procedures described by Hsiao et al. (2009), Raes et al. (2009) and Steduto et al. (2009). Transpiration is calculated as a function of the fraction of the soil area covered by the canopy of the crop and ETo, according to the equation of Allen et al. (1998).

$$T = SC^* \, Kc_{TR,x} \, ET_o \quad (4)$$

where: SC* = soil cover by the crop canopy adjusted for micro-advection, $m^2\ m^{-2}$; and $Kc_{TR,\ x}$ = crop coefficient under conditions of complete soil cover, dimensionless.

The percentage of soil cover (SC) was estimated weekly through the Canopeo application (Patrignani & Ochsner 2015). Ea is calculated in a similar way to that of ETa_{DUAL} and ETa_{RIT}, considering and adapting the two phases of water evaporation in the soil described by Allen et al. (1998), and the influence of soil cover is based on SC*.

Model performance analysis

The performance of the models was evaluated using the coefficient of determination (r^2), Nash-Sutcliffe efficiency index (NSE) (Nash & Sutcliffe 1970), mean bias error (MBE) and root-mean-square error (RMSE) (Richter et al. 2011, Willmott & Matsuura 2005).

MBE indicates when a model is underestimating or overestimating the observations, while RMSE indicates the differences between predicted values and observed values. The Nash-Sutcliffe index varies between -∞ and 1, where 1 corresponds to a perfect match of observed and modeled values and values lower than and equal to zero indicate that the model's predictions are as accurate as the average of the observed data (Schaefli & Gupta 2007). For Silva et al. (2008), NSE values above 0.36 are considered acceptable.

RESULTS AND DISCUSSION

Climatological data

Figure 1 shows the behavior of meteorological variables of the two experiments with soybean. In the winter experiment (Figure 1a), the values of minimum and maximum temperatures varied from 8 to 18.5 °C and from 22.5 to 32 °C, respectively. In the summer experiment (Figure 1b), the variations in these climatic variables were from 13.5 to 21 °C and from 26.2 to 37 °C, respectively. In the winter experiment, the accumulated thermal temperature (ATT) was equal to 838 °C, approximately 38.5% lower than the value obtained in the summer experiment. The number of daylight hours was 30% higher in summer than in winter.

In the winter experiment, the ETo values varied between 1.5 and 5.2 mm d^{-1}, while in the summer experiment this variation was between 1.9 and 7.1 mm d^{-1}. The value of ETo accumulated during the crop cycle in the winter experiment was equal to 329 mm, about 34% lower than the value verified in the summer experiment.

In the winter experiment, during the entire crop cycle, there were only three precipitation events (9, 10 and 11 DAS), which occurred when the crop was in the stage of emergence, totaling 9.5 mm. In the summer experiment, the total precipitation was equal to 418 mm, with higher concentration between 71 and 105 DAS, when the crop was in the intermediate and final development stages.

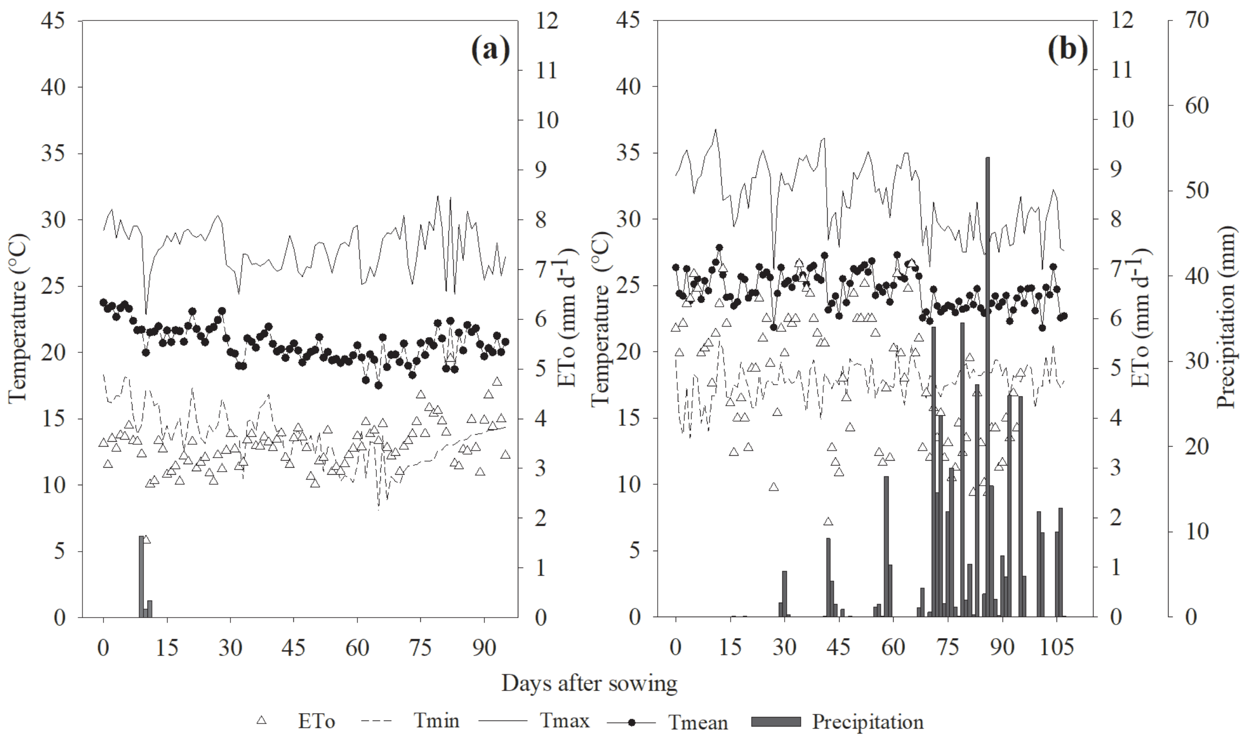

Figure 1. Maximum (Tmax), mean (Tmean) and minimum (Tmin) air temperatures, reference evapotranspiration (ETo) and precipitation observed in the winter (a) and summer (b) experiments.

Plant data

The values of the three parameters of the sigmoidal model, fitted to the root growth data for each of the treatments in the winter and summer experiments, are presented in Table I.

For the behavior of the parameter α (Table I), which represents the maximum root growth, there was a reduction of its value as the soil water deficit increases (T1 to T5) in both experiments. The highest root system depth was observed in T1 in the summer experiment, which was 14.3% greater than the root system depth observed in the winter experiment. From T1 to T5, the variations were equal to 45% in the winter experiment and to 38% in the summer experiment. The lowest depth was observed in T5, in the winter experiment, being 20% lower than the maximum root depth observed in T5, in summer.

This result, at first, is contrary to what was expected, that is, higher values of root system depth in treatments with higher water deficit. One possible explanation is that in treatments with higher deficit the volume of moist soil was smaller, an observation confirmed by the low values of moisture of the gravimetric samples taken during the studies. Thus, low moisture limited the volume of soil explored by the roots in search of water and nutrients, limiting their deepening.

In the winter experiment, the parameter b, which represents the level of data scattering, except for T1 to T2, decreased with the increase in soil water deficit. This behavior, however, was not observed in the summer experiment.

The parameter Xo, which represents the inflection point of the curve, that is, the point at which the maximum rate of variation of the function occurs, varied between 36 and 40 DAS in the winter experiment, for all treatments, while in the summer experiment, it varied from

Table I. Parameters of the sigmoidal model, fitted to root growth data, for each of the treatments in the winter and summer experiments for soybean crop.

Coef	Winter experiment					Summer experiment				
	T1	T2	T3	T4	T5	T1	T2	T3	T4	T5
α	36,85	33,53	29,83	25,28	20,39	43,96	40,76	38,33	31,47	27,23
b	15,75	15,77	14,60	12,59	11,56	25,27	24,64	24,80	26,97	27,77
Xo	36,11	36,95	38,75	38,33	39,51	39,60	39,93	41,95	44,58	45,64

Coef = coefficients, α = maximum root growth, b = scattering level and Xo = inflection point of the curve.

39 to 45 DAS. In both experiments, the highest value of Xo was observed in the T5 treatment.

The values of the three parameters of Gaussian Peak model, fitted to LAI data, for each of the treatments in the winter and summer experiments, are presented in Table II.

According to the performance of LAI, evidenced by the parameter α (Table II), there was a reduction of LAI as soil water deficit increased (T1 to T5) in both experiments. The highest values of LAI were observed in T1 treatments, being 72% higher in the summer experiment than in the winter experiment. In the winter experiment, a variation of 51% was observed from T1 to T5, whereas in summer this variation was 40%. The lowest values of LAI were observed in T5 in the winter experiment, being 52% lower than the LAI observed in T5, in summer.

In the winter experiment, the parameter b, which represents the peak width of the curve of the model, showed little variation with the increase in soil water deficit for the winter and summer experiments.

The parameter Xo, which represents the position of the peak the in relation to the days after sowing, showed that the highest values of LAI were reached between 70 and 73 DAS for the winter experiment and between 73 and 75 DAS for the summer experiment.

The increase in water restriction in the soil led to reduction in leaf area per soybean plant, generating plants with smaller canopy, resulting in lower demands of crop evapotranspiration. The lower growth of leaf area in treatments with greater restriction left the soil more exposed to evaporation, thus increasing the fraction of Ea over ETa under these conditions.

Accumulated actual evapotranspiration

The values of total ETa calculated by the gravimetric method and by the different models for all treatments, for the winter and summer experiments, are presented in Figure 2.

By analyzing the behavior of each model in the treatments of the winter experiment, it was possible to observe a trend of reduction in ETa, except for the model ETa_{RIT}, as the water deficit in the soil increased. ETa_{GRA}, in the T5 treatment, showed a reduction of 32% when compared to T1. For T2, T3 and T4, the reductions in ETa were on the order of 5, 13 and 19%, respectively, when compared to T1. ETa_{DUAL}, in the treatments T2, T3, T4 and T5, when compared to ETa_{GRA}, showed values about 1, 3, 11 and 17% lower, respectively. For the model ETa_{JEN}, there were reductions of 1, 2, 7 and 11% in T2, T3, T4 and T5, respectively. The model ETa_{ACRP}, in the treatments T2, T3, T4 and T5, showed reductions on the order of 7, 9, 12 and 23%, respectively, when compared to T1. The model ETa_{RIT}, despite having values 4 and 1% lower than those of ETa_{GRA} in the treatments T1 and T2, showed values 6, 13 and 24% higher than

Table II. Parameters of the Gaussian Peak model, fitted to LAI data, for each of the treatments in the winter and summer experiments, for soybean crop.

Coef	Winter experiment					Summer experiment				
	T1	T2	T3	T4	T5	T1	T2	T3	T4	T5
α	4,54	4,20	3,70	2,63	2,17	7,90	7,44	6,60	5,66	4,53
b	19,05	18,71	18,88	19,51	20,07	22,24	21,69	21,82	21,20	21,19
Xo	72,4	72,6	72,3	71,6	70,6	74,1	74,1	74,6	73,6	73,5

α = maximum leaf growth, b = peak width of the model curve and Xo = maximum peak position on the IAF in relation to the days after sowing.

those of ETa_{GRA} for T3, T4 and T5, respectively. Among the treatments, the difference between T1 and the others was on the order of 2%. Among the models, ETa_{RIT} was the one with the worst performance, especially for the treatments T4 and T5.

In the summer experiment, considering the values of ETa_{GRA} and of each model between treatments, it was observed that the values of total ETa_{GRA} ranged by 38% between T1 and T5 and was about 6% higher than in the winter experiment (Figure 2b). For the other treatments, the differences were 4, 13 and 26% for T2, T3 and T4, respectively. For the model ETa_{DUAL}, the difference was equal to 10% between T1 and T5 and to 1, 4 and 6% for T2, T3 and T4, respectively. A comparison between T1 and T5 in relation to ETa_{JEN} showed a reduction of 9%, being about 2% lower than the value observed in the winter experiment. For the other treatments, the differences between ETa_{JEN} and ETa_{GRA} ranged from 1 to 5%. The model ETa_{ACRP}, similarly to what was observed in the winter experiment, was the one which had total ETa variation closer to the values of ETa_{GRA}, and the differences between T1 and T2, T3, T4 and T5 were on the order of 7, 14, 19 and 25%, respectively. Finally, the behavior of the model ETa_{RIT} was similar to that in the winter experiment, with a small variation between treatments, on order of 3%. A possible explanation for the behavior observed in the ETa estimated by Ritchie model was a high irrigation frequency, which maintained Es throughout the experiment in phase 1 of soil water evaporation in both experiments. That is, the total volume evaporated did not exceed the value of the parameter U, equal to 13 mm. The value obtained for the parameter α, which represents evaporation in phase 2, was equal to 4.92 mm $d^{-0.5}$.

Also in Figure 2a, by analyzing the models within each treatment in the winter experiment, it was observed that in T1 the models ETa_{DUAL}, ETa_{JEN}, ETa_{ACRP} and ETa_{RIT} underestimated ETa by 4, 23, 15 and 4%, respectively, in comparison to the observed value. In the T2 treatment, the ETa estimated by the models ETa_{JEN} and ETa_{ACRP} underestimated the observed value by approximately 17%, while the model ETa_{RIT} underestimated it by 2%. The model ETa_{DUAL} showed a value equal to the observed value. For T3, the models ETa_{DUAL} and ETa_{RIT} overestimated the observed value by 12%, while the models ETa_{JEN} and ETa_{ACRP} underestimated it by 5 and 6%, respectively. In the T4 treatment, the overestimation of the observed value was equal to 3 and 11% by ETa_{DUAL} and ETa_{RIT}, whereas the models ETa_{JEN} and ETa_{ACRP} underestimated it by 10 and 9%, respectively. Finally, in the T5 treatment, the models ETa_{DUAL} and ETa_{RIT} overestimated

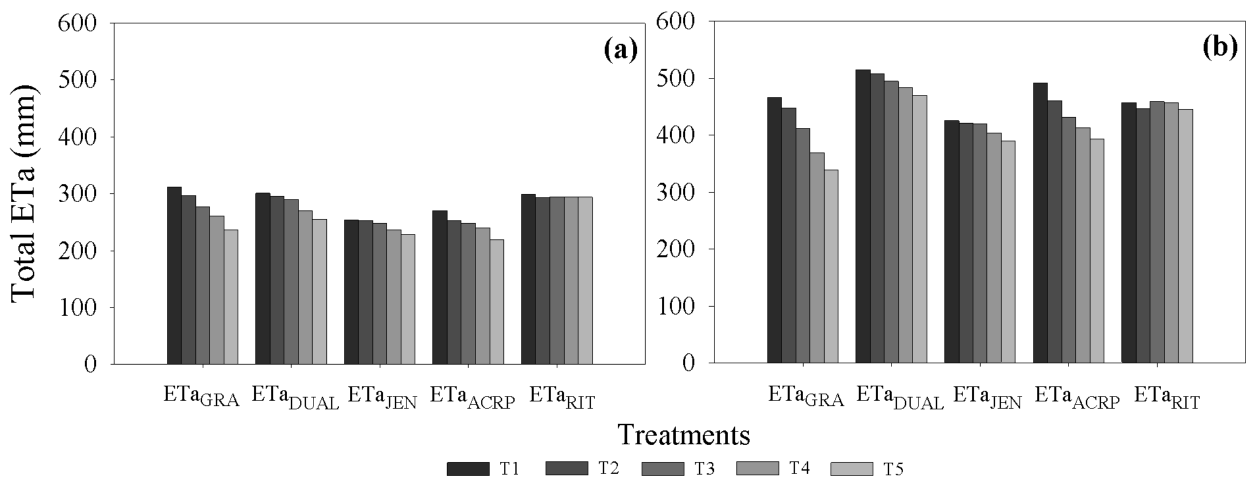

Figure 2. Total actual evapotranspiration observed (ETa_{GRA}) and estimated by the models FAO56 Dual (ETa_{DUAL}), Jensen and Heermann (ETa_{JEN}), AquaCrop (ETa_{ACRP}) and Ritchie (ETa_{RIT}) of soybean crop calculated for the treatments [T1: water available in the soil (AW) of the 80-100%; T2: 60-80% AW; T3: 40-60% AW; T4: 20-40% AW and T5: 0-20% AW)] in the winter (a) and summer (b) experiments.

ETa by 7 and 20%, while ETa_{JEN} and ETa_{ACRP} underestimated it by 4 and 9%, respectively.

In the summer experiment, also analyzing the models within each treatment, the ETa calculated by ETa_{JEN} and ETa_{RIT}, for treatment T1, was underestimated by 10% and 2%, while the models ETa_{DUAL} and ETa_{ACRP} overestimated the values of ETa_{GRA} by 9 and 5%, respectively. In T2, while the model ETa_{RIT} showed a value equal to that of ETa_{GRA}, and ETa_{JEN} underestimated ETa_{GRA} by 6%, the models ETa_{DUAL} and ETa_{ACRP} overestimated it by 12 and 3%, respectively. The models ETa_{DUAL}, ETa_{JEN}, ETa_{ACRP} and ETa_{RIT} overestimated ETa_{GRA} by 17, 2, 5 and 10%, for the treatment T3, by 24, 8, 11 and 19%, for T4, and by 28, 13, 14 and 24%, for T5, respectively (Figure 2b).

The difference observed in ETa estimation by the models can be attributed to their different approaches, both under the conditions without water restriction and within the different ranges of water stress in the soil. Although some models use the same variable within their routines to calculate ETa, such as the use of ETo by the models ETa_{DUAL}, ETa_{JEN} and ETa_{ACRP}, and the use of ET_{MAX} by the model ETa_{RIT}, both to account for the evapotranspiration demand of the environment, other variables show different approaches, such as the use of LAI by the model ETa_{RIT}, percentage of soil cover by ETa_{ACRP} and the coefficients Kcb, Ks and Ke by the models ETa_{DUAL} and ETa_{JEN}.

The model ETa_{JEN} underestimated the observed values of ETa for all treatments in the winter experiment and for the treatments T1 and T2 in the summer experiment. The underestimation is probably be due to the way in which the model calculates the Ke coefficient, assuming values of (0.9 − Kcb) 0.8; (0.9 − Kcb) 0.5; (0.9 − Kcb) 0.3, after the first, second and third days after rain or irrigation, respectively. With this approach, Ke values can vary, already on the first day after rain or irrigation, between 0 (Kcb = 0.9) and 0.72 (Kcb = 0). Under the same conditions, using the Ke equation proposed by Allen et al. (1998), for Kcb equal to zero the Ke value will be 1.10, which is 53% greater than the maximum Ke value of the model of Jensen et al. (1971). For the maximum values of Kcb, 0.9 for Jensen's model and 1.10 for the FAO56 Dual model, Ke values became equal to 0. However, for the FAO56 Dual model, Kcb values = 0.9, under

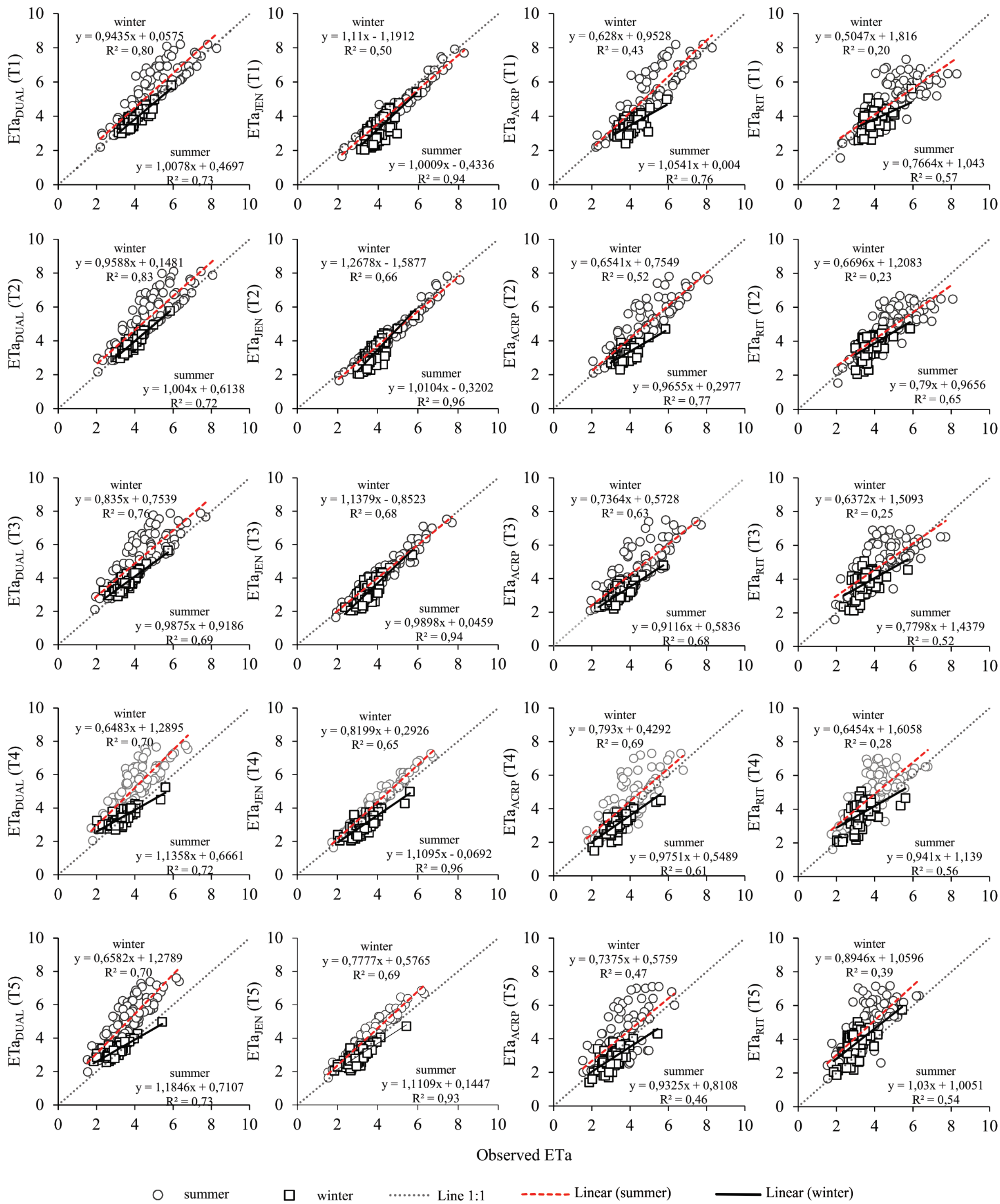

Figure 3. Comparison between values of actual evapotranspiration of soybean crop observed (ETa_{GRA}) and estimated by the models FAO56 Dual (ETa_{DUAL}), Jensen and Heermann (ETa_{JEN}), AquaCrop (ETa_{ACRP}) and Ritchie (ETa_{RIT}) for the treatments [T1: water available in the soil (AW) of the 80-100%; T2: 60-80% AW; T3: 40-60% AW; T4: 20-40% AW and T5: 0-20% AW)] in winter and summer experiments.

the conditions of this study, resulted in Ke ≅ 0.27. As lower values of Ke imply lower values of ETa, it was observed in the initial phase of the two experiments that the Ke values, determined by Jensen, were on average 64% lower for T1 and 40% lower for T5 than the Ke calculated by the FAO56 Dual model.

In the case of ETa_{ACRP}, there was high sensitivity of the model to the variations of SC, which, in order to better represent reality, was converted into the actual canopy cover adjusted for micro-advection effects (SC*), by means of a third-order polynomial function.

The low sensitivity of Ritchie model to the increase in soil moisture deficit can be explained by the high frequency of irrigation, which kept the soil surface always moist, that is, the model remained, until complete soil cover, always in phase 1 evaporation, that is, with high rates of Es.

Actual daily evapotranspiration

ETa, in the T1 treatment of the winter experiment, calculated by the models ETa_{DUAL}, ETa_{JEN}, ETa_{ACRP} and ETa_{RIT}, showed daily values ranging from 2.9 mm d^{-1} (minimum value) to 5.8 mm d^{-1} (maximum value), 2.0 to 5.4 mm d^{-1}, 2.4 to 5.0 mm d^{-1} and 2.6 to 5.6 mm d^{-1}, respectively. For the summer experiment, following the same order, the variation was 2.2 to 8.2 mm d^{-1}; 1.7 to 7.9 mm d^{-1}; 2.2 to 8.2 mm d^{-1} and 1.6 to 7.3 mm d^{-1}. ETa_{GRA} ranged from 2.2 to 8.3 mm d^{-1}.

Figure 3 shows the relationship between the actual evapotranspiration estimated by the FAO56 Dual models, Jensen and Heermann, AquaCrop and Ritchie and the observed ETa.

Based on the values of r^2, which ranged from 69 to 82%, it was observed that, in the winter experiment, in all treatments, ETa was better estimated by the model ETa_{DUAL}. The next models were ETa_{JEN} and ETa_{ACRP}, with r^2 values ranging from 49 to 68%. Among the models evaluated, ETa_{RIT} was the one that showed the worst performance for all treatments, with r^2 ranging from 19 to 38% (Figure 3).

In summer, the model ETa_{JEN} was the one that best estimated ETa, with r^2 values ranging between 93 and 96%. The next model was ETa_{DUAL}, followed by ETa_{ACRP}, with r^2 ranging from 46 to 77%. Although it had higher values of r^2 than in the winter experiment, ETa_{RIT} continued to show the worst performance in determining ETa in the summer.

According to the trend line of the models in relation to the 1:1 line (Figure 3) and the MBE values presented in Table III for the winter and summer experiments, it was observed that the models ETa_{DUAL}, ETa_{JEN}, ETa_{ACRP} and ETa_{RIT} underestimated ETa_{GRA}. In the winter experiment, it was observed, in the T1 treatment, that ETa_{DUAL} (MBE = -0.17), ETa_{JEN} (MBE = -0.75), ETa_{ACRP} (MBE = -0.54) and ETa_{RIT} (MBE = -0.16) underestimated the values of ETa_{GRA}. In the T2 treatment, ETa_{GRA} values were underestimated only by the models ETa_{JEN}, ETa_{ACRP} and ETa_{RIT}. The model ETa_{DUAL} did not differ from the observed value. In the T3 treatment, the models ETa_{DUAL} and ETa_{RIT} overestimated the values of ETa_{GRA}, while ETa_{JEN} and ETa_{ACRP} showed underestimation. The treatments T4 and T5 showed behavior similar to that of T3 for the models that underestimated and overestimated ETa_{GRA}.

For the summer experiment, ETa was underestimated by ETa_{JEN}, in the treatments T1 and T2, and ETa_{RIT}, in the treatment T1. The model ETa_{RIT}, in the treatment T2, and the model ETa_{JEN}, in the treatment T3, were equal to the value of ETa_{GRA}. In the other treatments, ETa was overestimated by the models.

Table III presents the indicators of performance of the models for all treatments in the two experiments evaluated. The models ETa_{DUAL}, in the treatments T3 (NSE = 0.60) and T4 (NSE = 0.42), ETa_{JEN}, in T3 (NSE = 0.38) and T5

Table III. Performance indicators for the models FAO56 Dual (ETa_{DUAL}), Jensen and Heermann (ETa_{JEN}), AquaCrop (ETa_{ACRP}) and Ritchie (ETa_{RIT}) in the estimation of the actual evapotranspiration of soybean crop, considering the treatments [T1: water available in the soil (AW) of the 80-100%; T2: 60-80% AW; T3: 40-60% AW; T4: 20-40% AW and T5: 0-20% AW)].

Treatment	Model	winter			summer		
		NSE	RMSE	MBE	NSE	RMSE	MBE
T1	ETa_{DUAL}	0,67	0,27	-0,17	0,62	0,93	0,51
	ETa_{JEN}	-0,61	0,91	-0,75	0,84	0,53	-0,43
	ETa_{ACRP}	-1,25	0,65	-0,54	0,73	0,80	0,27
	ETa_{RIT}	-0,10	0,54	-0,16	0,51	0,91	-0,09
T2	ETa_{DUAL}	0,83	0,20	0,00	0,54	1,01	0,63
	ETa_{JEN}	-0,03	0,71	-0,57	0,92	0,37	-0,27
	ETa_{ACRP}	-1,50	0,65	-0,56	0,76	0,68	0,14
	ETa_{RIT}	0,20	0,51	-0,05	0,61	0,77	0,00
T3	ETa_{DUAL}	0,60	0,29	0,17	0,33	1,19	0,87
	ETa_{JEN}	0,38	0,53	-0,36	0,94	0,31	0,00
	ETa_{ACRP}	-0,10	0,47	-0,36	0,65	0,80	0,20
	ETa_{RIT}	0,04	0,60	0,22	0,34	1,06	0,49
T4	ETa_{DUAL}	0,42	0,33	0,11	0,01	1,41	1,19
	ETa_{JEN}	0,32	0,46	-0,31	0,87	0,44	0,35
	ETa_{ACRP}	0,39	0,41	-0,26	0,49	0,95	0,45
	ETa_{RIT}	-0,19	0,74	0,42	0,09	1,27	0,91
T5	ETa_{DUAL}	0,16	0,38	0,24	-0,28	1,54	1,36
	ETa_{JEN}	0,59	0,31	-0,10	0,70	0,62	0,54
	ETa_{ACRP}	0,26	0,48	-0,22	0,28	1,15	0,57
	ETa_{RIT}	-0,60	0,95	0,74	-0,11	1,45	1,11

(NSE = 0.59), and ETa_{ACRP}, in the treatment T4 (NSE = 0.39), showed satisfactory performance, according to the classification proposed by Silva et al. (2008).

In the summer experiment, in general, considering as a criterion the NSE > 0.36, the models showed satisfactory performance, except for ETa_{DUAL} and ETa_{RIT} in T3, T4 and T5, and ETa_{ACRP} in the treatment T5.

Based on Table III, in the winter experiment, it was observed that among the models, ETa_{DUAL} was the one which showed the lowest error in the estimation of ETa_{GRA} values, for the treatments T1 (RMSE = 0.27 mm d^{-1}), T2 (RMSE = 0.20 mm d^{-1}), T3 (RMSE = 0.29 mm d^{-1}) and T4 (RMSE = 0.33 mm d^{-1}), while for T5 (RMSE = 0.31 mm d^{-1}), the model ETa_{JEN} performed better than the others. In the summer experiment, ETa_{JEN} showed lower values of RMSE for all treatments, from 0.31 mm d^{-1} (T3) to 0.62 mm d^{-1} (T5). For the winter experiment, the highest values of RMSE were obtained with the models ETa_{JEN}, for the treatments T1 (RMSE

= 0.91 mm d^{-1}) and T2 (RMSE = 0.71 mm d^{-1}), and ETa_{RIT}, for the treatments T3 (RMSE = 0.60 mm d^{-1}), T4 (RMSE = 0.74 mm d^{-1}) and T5 (RMSE = 0.95 mm d^{-1}). In the summer experiment, the model ETa_{DUAL} showed the worst performance in all treatments, with RMSE values ranging from 0.93 mm d^{-1}, in the treatment T1, to 1.54 mm d^{-1}, in the treatment T5.

Dhiambo & Irmak (2012), when evaluating for the State of Nebraska, USA, the ETa estimated by the methods of Bowen ratio and ETa_{DUAL}, for soybean crop, found r^2 values of 0.64 and 0.75 for the years 2007 and 2008, respectively. Both studies were conducted under a similar condition to those of the treatments T1 and T2 of the present study, where r^2 was 0.82 and 0.66, respectively.

The model ETa_{DUAL} has been evaluated in different regions of the world, but for crops other than soybean, it showed satisfactory results. Er-Raki et al. (2010) obtained RMSE values of 0.54 and 0.71 mm d^{-1} and MBE values of 0.02 and 0.05 mm d^{-1}, for the years 2003 and 2004, respectively, when they evaluated ETa estimation by ETa_{DUAL} compared to ETa estimated by Eddy Covariance for olive grown in Morocco. Paredes et al. (2018), studying the model ETa_{DUAL} for potato crop under the conditions of southern Italy, found r^2 of 0.93 and RMSE of 0.87 mm d^{-1}.

CONCLUSIONS

In the winter experiment, the model FAO56 Dual showed the best performance in the estimation of the actual evapotranspiration of soybean crop for most treatments, with NSE ranging from 0.42 to 0.83. In the sequence, with better performance, are the models of Jensen and Heermann (NSE ranging from 0.38 to 0.59), followed by AquaCrop (NSE = 0.39 for treatment T4).

In the summer experiment, the Jensen and Heermann model showed the best performance in the estimation of actual evapotranspiration (NSE ranging from 0.70 to 0.94), followed by AquaCrop (NSE ranging from 0.49 to 0.76), FAO56 Dual (NSE ranging from 0.54 to 0.62) and Ritchie (NSE ranging from 0.51 to 0.61).

In general, considering the two experiments, the Jensen and Heermann model, with mean NSE of 0.65, was the one which best represented the actual evapotranspiration of soybean crop in the Cerrado region, followed by the FAO56 Dual model, with mean NSE of 0.60. The AquaCrop model stands out with a mean NSE of 0.48. Ritchie model only performed well in the summer experiment.

Among the evaluated models, Ritchie model showed, in general, the worst performance in the estimation of actual evapotranspiration.

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