



Evaluation of alternative methods to calculate evapotranspiration and their impact on soybean yield estimation

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ABSTRACT

Despite the several studies comparing methods for evapotranspiration (ET_o) estimation, scientific reports demonstrating their use and evaluation when coupled to agrometeorological models have not been analyzed, particularly in regard to the comparison of the estimated results obtained in the modeling with the real production data experimentally obtained in the field. The present study evaluated nine alternative methods to calculate ET_o for estimating soybean yield, associated with actual yields obtained in irrigated and non-irrigated fields, at three sowing periods during the 2013/14 crop season in Southern Brazil. All methods were evaluated in relation to the standard Penman–Monteith method. Their performance was measured through regression analysis and statistical coefficients submitted to the Tukey test. ET_o values obtained through the alternative methods were used to calculate water balances for soybean, considering irrigated and non-irrigated environments. Theoretical and real potential yields were higher in later sowings. The Priestley–Taylor method was the best to estimate daily ET_o alternatively to that recommended by FAO (Penman–Monteith). On the other hand, the alternative method of Thornthwaite–Camargo was the best for estimations at 10-day periods, in all sowing dates. Furthermore, the methods of Thornthwaite–Camargo, Benevides–Lopez, Camargo, and Thornthwaite showed the smallest deviations to estimate ET_o (10-day periods) for calculating actual yields (Y_a).

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Introduction

Crop yield estimation is a strategic tool for economic management, public policies and food safety of a country, mainly under drought conditions. According to Gomes et

al. (2014), agricultural projections integrate the most relevant information to support agricultural activities, and they are usually based on agrometeorology. Crop yield variability has been mainly related to water availability, with

major impacts compared to pests and diseases (Hoogenboom, 2000; Farias et al., 2001; Assad et al., 2007).

The water balance calculation has been largely used to measure water availability in agricultural systems (Battisti et al., 2013; Monteiro & Sentelhas, 2014; Vianna & Sentelhas, 2014; Saray et al., 2020). The reference evapotranspiration (ET_o) is used in calculations, and if it is not measured directly by a lysimeter this variable may be estimated through meteorological elements measured in weather stations (Carvalho et al., 2015). There are different methods to estimate ET_o, and the choice of method depends on a series of factors, such as data availability and desired time scale (Borges & Mendiondo, 2007; Silva et al., 2017; Tegos, 2019).

The Food and Agriculture Organization of the United Nations (FAO) recommends the use of the Penman-Monteith method as standard to estimate daily evapotranspiration (Allen et al., 1998). However, this method uses several parameters not always observed or measured in weather stations, thus encouraging studies to establish more simplified alternative methods for evapotranspiration estimation (Borges Júnior et al., 2012; Pilau et al., 2012; Bezerra et al., 2014; Oliveira et al., 2020).

Some mathematical (current agrometeorological) models may act as efficiency indicators, since they consider the action of each meteorological element on crop yield, which can be described (Araujo et al., 2011; Silva et al., 2011; Gomes et al., 2014; Sentelhas et al., 2015; Silva et al., 2020). Thus, agrometeorological modeling involves the action of meteorological elements observed on crop traits, aggregating biomass accumulation or loss over time. The Agro-Ecological Zone Model (Doorenbos & Kassam, 1994) estimates the loss of yield at different developmental stages, according to the crop sensitivity to water stress.

It is important to know the evapotranspiration demand in agriculture, since water management and yield may be improved due to the reliability of methods chosen to estimate crop evapotranspiration (Fernandes et al., 2012). Despite the several studies comparing methods for ET_o estimation, there are no scientific reports demonstrating their use and evaluation in agrometeorological modeling aimed at estimate crop production compared to experimental data obtained in the field.

In order to identify more reliable methods for field-measured yields, for purposes of agrometeorological modeling, the present study evaluated nine alternative methods to calculate ET_o for estimating soybean yield, associated with actual yields obtained in irrigated and non-irrigated environments, at three sowing periods during the 2013/14 crop season in Southern Brazil.

Material and methods

The study site comprises the geographic limits of Londrina, an important soybean-producing municipality located in Northern Paraná State (PR), Southern Brazil, the climate of which is classified as Cfa according to the Köppen Climate Classification System (Alvares et al., 2013). In the present study, we used information obtained in the automatic weather station belonging to the Brazilian Agricultural Research Corporation - National Soybean Research Center (Embrapa Soybean), described by Sibaldelli et al. (2020), located at 23°11' S, 51°11' W and 630 m altitude.

The crop data comprise soybean production obtained in the crop season 2013/2014. The cultivar BRS-284 was sown on three dates (Oct 10, 2013; Nov 01, 2013; Nov 21, 2013), in irrigated and non-irrigated plots in the experimental field at Embrapa Soybean, Londrina, PR, Brazil. The dates were chosen according to the recommendations of the Agricultural Climate Risk Zoning (MAPA, 2020). Both trials were set in a randomized complete block design, with three blocks, and followed the soybean production technologies described and recommended by Embrapa Soybean (Embrapa Soja, 2013).

The crop season 2013/2014 was peculiarly characterized by a severe drought in the reproductive period of the crop in the experimental field at Embrapa Soybean, discussed by Crusiol et al. (2017). This characteristic was corroborated with the greater contrast in the comparison between the data production estimated in the agrometeorological modeling and the actual yield data experimentally obtained in the field.

Meteorological data were collected hourly between Oct 2013 and Mar 2014, the period recommended for soybean cultivation in that region. The meteorological elements used were mean, maximum and minimum temperature, relative humidity, rainfall, daily global solar radiation (R_s), and wind speed at 2 m height.

These data were used in daily and 10-day period scales at three sowing dates (Oct 10, 2013; Nov 01, 2013; Nov 21, 2013) in Londrina, PR, during the 2013/2014 crop season.

Nine alternative methods for ET_o estimation were evaluated in relation to the standard Penman-Monteith method, parameterized and recommended by FAO (Allen et al., 1998), as the equation (1):

$$ET_o \text{ (PM)} = \frac{0.408 \times s \times (R_n - G) + \frac{\gamma \times 900 \times U_2 \times (e_s - e_a)}{T + 273}}{s + \gamma \times (1 + 0.34 \times U_2)} \quad (1)$$

$$e_s = 0.6108 \times e^{\frac{17.27 \times T}{237.3 + T}} \quad (2)$$

$$e_a = \frac{UR \times e_s}{100} \quad (3)$$

$$s = \frac{4098 \times es}{(T + 237.3)^2} \quad (4)$$

where ETo (PM) is the reference evapotranspiration for grass (mm day⁻¹); *s* represents the slope of the saturation vapor pressure temperature relationship (kPa °C); Rn is the net radiation (MJ m⁻² day⁻¹); *G* is the soil heat flux (MJ m⁻² day⁻¹), considered null; *T* is the daily mean air temperature (°C) at 2 m, based on the average of maximum and minimum temperatures; *U*₂ is the daily mean wind speed at 2 m (m s⁻¹); *es* is the saturated vapor pressure (kPa); *ea* is the actual vapor pressure (kPa); *UR* is the daily mean relative air humidity (%); (*es*-*ea*) represents the saturation vapor pressure deficit (Δe , kPa); and γ is the psychrometric constant (constant value equal to 0.06215 kPa °C).

The following equations were used for estimating the net radiation (Rn), as recommended by Allen et al. (1998) and described by Sentelhas et al. (2010):

$$Rn = Rns - Rnl \quad (5)$$

$$Rns = 0.77 \times GSR \quad (6)$$

$$Rnl = \left[\sigma \left(\frac{T_{max_k}^4 + T_{min_k}^4}{2} \right) \times (0.34 - 0.14 \times \sqrt{ea}) \times \left(1.35 \times \frac{GSR}{GSRo} - 0.35 \right) \right] \quad (7)$$

$$GSRo = 0.75 \times Ra \quad (8)$$

where Rns is the net shortwave radiation (MJ m⁻² day⁻¹); Rnl is the net longwave radiation (MJ m⁻² day⁻¹); GSR is the global solar radiation (MJ m⁻² day⁻¹); σ is the Stefan-Boltzmann constant (4.903 × 10⁻⁹ MJ K⁻⁴ m⁻² day⁻¹); *T*_{max_k} is the maximum temperature (K); *T*_{min_k} is the minimum temperature (K); GSR/GSRo is the ratio between the global solar radiation and the clear-sky solar radiation (MJ m⁻² day⁻¹, ≤1); and *Ra* is extraterrestrial radiation (MJ m⁻² day⁻¹).

The nine alternative methods evaluated for ETo estimation were:

a) Priestley-Taylor (1972) apud (Caporusso & Rolim, 2015; Sentelhas et al., 2010):

$$ETo (PT) = 1.26 \times \frac{s}{s+\gamma} \left(\frac{Rn-G}{\lambda} \right) \quad (9)$$

where λ is the latent heat of vaporization (2.45 MJ kg⁻¹).

b) Makking (1957) apud (Pilau et al., 2012):

$$ETo (MAK) = 0.61 \times W \times \frac{GSR}{2.45} - 0.12 \quad (10)$$

$$W = 0.407 + 0.0145 \times T \text{ for } 0 \text{ } ^\circ\text{C} < T < 16 \text{ } ^\circ\text{C} \quad (11)$$

$$W = 0.483 + 0.01 \times T \text{ for } 16.1 \text{ } ^\circ\text{C} < T < 32 \text{ } ^\circ\text{C} \quad (12)$$

where *W* is the weighting factor as a function of *T*, calculated according to the equations 11 and 12.

c) Hamon (1961) apud (Caporusso & Rolim, 2015):

$$ETo (H) = 0.55 \times \left(\frac{N}{12} \right) \times \left(\frac{4.95 \times e^{0.062 \times T}}{100} \right)^2 \times 25.4 \quad (13)$$

$$N = \frac{2 \times hn}{15} \quad (14)$$

where *hn* is the sunrise time; *N* is the photoperiod (h).

d) Tanner-Pelton (1960) apud (Caporusso & Rolim, 2015):

$$ETo (TP) = 1.12 \times \left[\left(\frac{Rn \times 100}{4.18} \right) \div 59 \right] - 0.11 \quad (15)$$

e) Benevides-Lopez (1970) apud (Caporusso & Rolim, 2015):

$$ETo (BL) = 1.21 \times 10^{\frac{7.5 \times T}{237.5 + T}} \times (1 - 0.01 \times RH) + 0.21 \times T - 2.3 \quad (16)$$

f) Thornthwaite (1948) apud (Pilau et al., 2012; Sentelhas et al., 2010):

$$ETo (TH) = 16 \times \left(10 \times \frac{T}{I} \right)^a \times \left(\frac{N}{12} \times \frac{ND}{30} \right) \quad (17)$$

$$I = 12 \times (0.2 \times Ta)^{1.514} \quad (18)$$

$$a = 0.4924 + 1.79 \times 10^{-2} \times I - 7.71 \times 10^{-5} I^2 + 6.75 \times 10^{-7} I^3 \quad (19)$$

where *I* is the heat index of the region; *Ta* is the climate normal annual mean temperature; *a* is a cubic function of *I*; and *ND* is the number of days in the period (days).

g) Thornthwaite-Camargo (1999) apud (Pilau et al., 2012; Sentelhas et al., 2010):

$$ETo (THC) = 16 \times \left(10 \times \frac{Tef}{I} \right)^a \times \left(\frac{N}{12} \times \frac{ND}{30} \right) \quad (20)$$

$$Tef = 0.36 \times (3 \times Tmax - Tmin) \quad (21)$$

where *T*_{ef} is the daily effective temperature (°C); *T*_{max} is the maximum air temperature (°C); and *T*_{min} is the minimum air temperature (°C).

h) Camargo (1971) apud (Pilau et al., 2012; Caporusso & Rolim, 2015):

$$ETo (CAM) = 0.01 \times \frac{Ra}{2.45} \times T \times ND \quad (22)$$

i) Hargreaves–Samani (1985) apud (Pilau et al., 2012; Caporusso & Rolim, 2015):

$$ETo (HS) = 0.0023 \times \frac{Ra}{2.45} \times (Tmax - Tmin)^{0.5} \times (T + 17.8) \quad (23)$$

The performances of these methods were measured through regression analysis. The R^2 values were obtained by forcing the linear regression coefficient to pass through the origin ($y = bx$). These values do not represent the precision of an equation for estimating a method as a function of a standard one, but it is the method adjustment precision in relation to a 1:1 straight line. Negative values indicate no relation between methods. Furthermore, the higher the negative value, the higher the dispersion.

The b values indicate the accuracy of the alternative methods in relation to the standard Penman–Monteith method. R^2 values can be considered as precision measurements, so that the perfect method should have $b = 1$ and $R^2 = 1$ (Sentelhas et al., 2010). Thus, for performance analysis, the results of the following statistical coefficients were obtained in scales of 24 h and 10-day periods: accuracy (b), determination (R^2), agreement (d), confidence (c), and Pearson correlation (r).

The Willmott's index of agreement or d index (Willmott, 1981) ranges from 0 to 1, indicating the distance between the values estimated by the alternative methods and those estimated by the Penman–Monteith method. The use of the mean bias error (MBE) and the d index consists an appropriate evaluation of the statistical performance of estimation models, with simultaneous analyses of mean deviation, thus allowing under- or overestimations to be identified, in addition to spreading and adjustment of models in relation to measured values (Souza et al., 2011; Carvalho et al., 2015; Oliveira et al., 2020). On the other hand, confidence statistical indices (c) were classified as shown in Table 1.

The difference between the evapotranspiration obtained through an alternative method and that of Penman–Monteith method may be represented by a deviation. Thus, MBE provides information about the long-term alternative method performance, in which the value tending to zero is ideal. According to Carvalho et al. (2015), MBE represents the mean deviation. Furthermore, the lower the absolute value, the better the method performance. In addition, negative values indicate underestimations and vice versa (Alves & Vecchia, 2011; Carvalho et al., 2015). MBE values were obtained through the equation:

Table 1. Performance analysis between the Penman–Monteith method and those proposed for estimating the reference evapotranspiration through the confidence statistical index (c) (Cecilio et al., 2012).

c value	Performance
≥ 86	Great
0.76 to 0.85	Very good
0.66 to 0.75	Good
0.51 to 0.65	Regular
0.41 to 0.50	Bad
≤ 0.40	Awful

$$MBE = \frac{1}{n} \sum_{i=1}^n (ETo_{estimated} - ETo_{PM}) \quad (24)$$

To check statistical differences among performances of proposed methods, MBE values were submitted to the Tukey test ($p \leq 0.05$).

The ETo values of each alternative method were used in calculations of 10-day period water balances for soybean in irrigated and non-irrigated environments (Thorntwaite & Mather, 1955). The crop cycle was considered as 120 days, divided into four phenological stages in their respective 10-day periods, which were evaluated and adapted to the crop cycle as described by Farias et al. (2001). Considering the management characteristics of the study region, the soil water holding capacity (SWHC) in the soil was set as 75 mm. The obtained ETo values were multiplied by the specific crop coefficients (Kc) for each phenological phase (Farias et al., 2001), thus obtaining the maximum crop evapotranspiration (ETc).

The maximum yield (Y_m) was estimated through the Agro-Ecological Zone method (Doorenbos & Kassam, 1994). The actual yield (Y_a) was estimated based on penalizing the maximum yield (Y_m) by water deficit (Assad et al., 2007; Battisti et al., 2013; Sentelhas et al., 2015), and the actual crop evapotranspiration (ETa) values were used in calculations from each alternative method evaluated.

The results obtained through agrometeorological modeling of maximum and actual theoretical yields were compared with field-obtained real data.

Results and discussion

Daily-Scale Performance

Regarding daily-scale ETo estimations, the PT method showed better accuracy for sowing on Oct 10 ($b = 1.04$), followed by the methods BL ($b = 0.94$) and MAK ($b = 0.80$), which tended to underestimate the obtained values, whi-

Table 2. Statistical performance of methods proposed for daily ETo estimation in relation to the standard Penman–Monteith method, considering accuracy (b), precision (R²), agreement (d), confidence (c), and correlation (r). Sowing dates were on Oct 10, Nov 01 and Nov 21 in the 2013/2014 crop season in Londrina, PR, Brazil. The methods were: Priestley–Taylor (PT), Makkink (MAK), Hamon (H), Tanner–Pelton (TP), Benevides–Lopez (BL), Thornthwaite (TH), Thornthwaite–Camargo (THC), Camargo (CAM), and Hargreaves–Samani (HS).

Sowing dates	Coefficients	PT	MAK	H	TP	BL	TH	THC	CAM	HS
Oct 10	b	1.04	0.80	-	1.29	0.94	-	-	-	-
	R ²	0.74	0.89	-	0.68	0.55	-	-	-	-
	d	0.73	0.58	-	0.49	0.67	-	-	-	-
	c	0.86	0.79	-	0.67	0.66	-	-	-	-
	r	0.91	0.94	-	0.89	0.76	-	-	-	-
Nov 01	b	1.05	0.80	-	1.29	0.97	-	-	-	-
	R ²	0.75	0.89	-	0.68	0.56	-	-	-	-
	d	0.74	0.59	-	0.49	0.67	-	-	-	-
	c	0.87	0.80	-	0.67	0.66	-	-	-	-
	r	0.92	0.95	-	0.90	0.76	-	-	-	-
Nov 21	b	1.07	0.80	-	1.30	1.02	-	-	-	-
	R ²	0.83	0.91	-	0.76	0.59	-	-	-	-
	d	0.76	0.62	-	0.51	0.67	-	-	-	-
	c	0.89	0.83	-	0.71	0.70	-	-	-	-
	r	0.94	0.96	-	0.91	0.79	-	-	-	-

le the method TP (b = 1.29) tended to overestimate them (Table 2).

On the sowing dates Nov 01 and 21, 2013, respectively, the best accuracy values were obtained through the method BL (0.97; 1.02), followed by PT (1.05; 1.07), MAK (0.80; 0.80), once more tending to underestimate data, and TP (1.29; 1.30), which overestimated ETo values.

The MAK method was the most precise in all sowing dates based on R² values (0.89; 0.89; 0.91, respectively), with a “very good” confidence statistical index. In daily scale, this result corroborates those of other authors who also indicated such a method as precise and showing great performance (Conceição & Mandelli, 2005; Pilau et al., 2012). After, the PT method presented precision values equal to 0.74, 0.75 and 0.83, respectively, thus receiving “great” classification in all sowing dates. These results are in agreement with other studies that analyzed this method as an alternative (Caporusso & Rolim, 2015; Silva et al., 2017; Farias et al., 2020; Oliveira et al., 2020).

Low R² values were shown by the methods TP (0.68; 0.68; 0.76) and BL (0.55; 0.56; 0.59), classified as “good” according to the confidence statistical index (c). The low values of the BL method were also discussed by Silva et al. (2017), who recommended the use of this method with caution. The values of the Pearson correlation coefficient (r) on different sowing dates were, respectively: MAK (0.94; 0.95; 0.96), PT (0.91; 0.92; 0.94), TP (0.89; 0.90; 0.91), and BL (0.76; 0.76; 0.79).

Although originally recommended for monthly or 10-day period scales, the other methods were also used for daily ETo estimation. However, they were not considered because they do not present relation when compared to

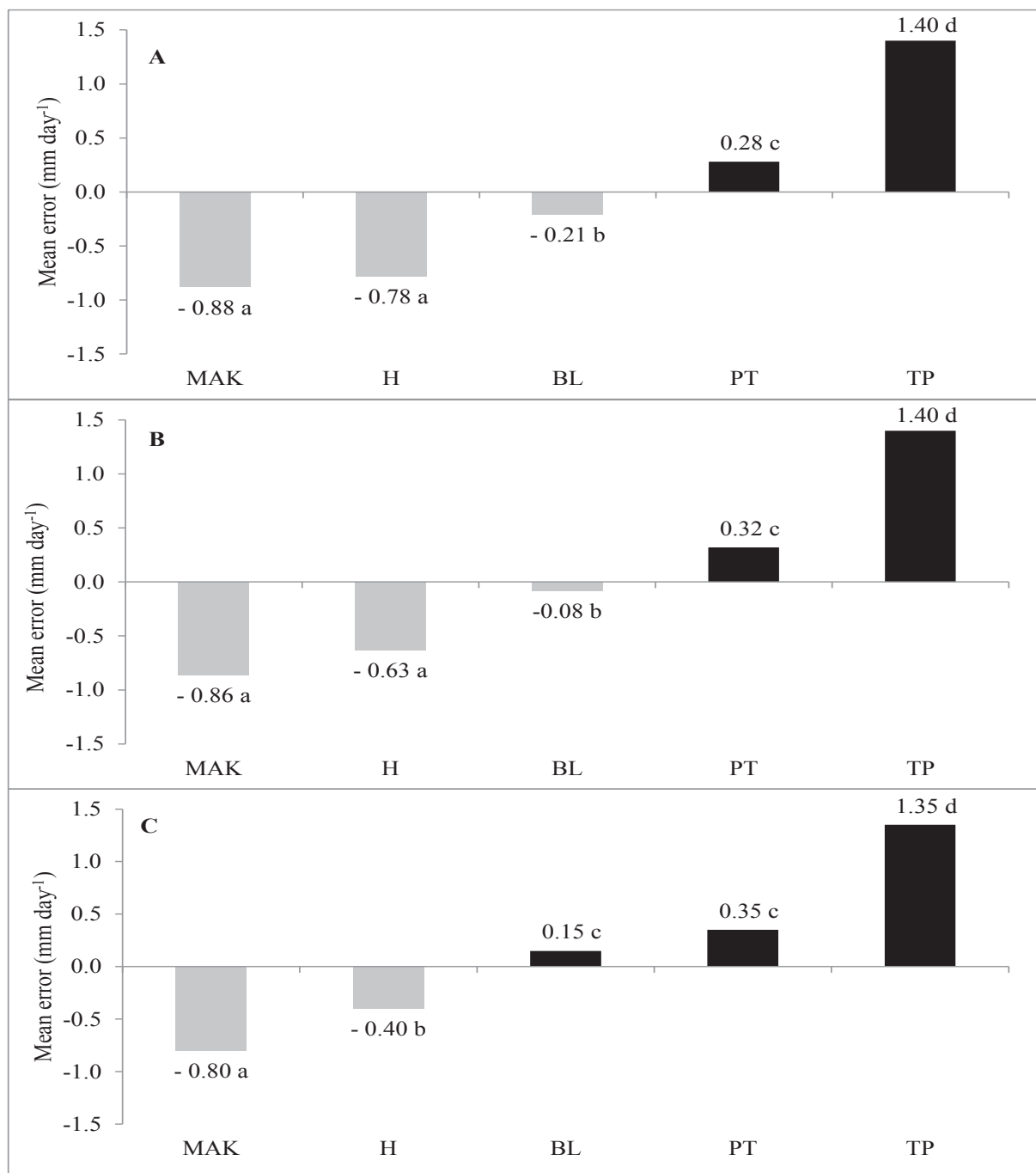
the standard Penman–Monteith method. Similarly, other authors demonstrated limitations for the use of the methods Thornthwaite–Camargo and Thornthwaite in municipalities of Rio Grande do Sul State, Brazil, in daily scale (Pilau et al., 2012).

Since MBE values met the assumptions of the analysis of variance, they were submitted to the Tukey test (p ≤ 0.05). In daily scale, the five methods showing the best performance for ETo estimation were evaluated (Figure 1). The methods MAK and H underestimated ETo values, presenting statistical difference only on the latest sowing (Nov. 21).

MBE values decreased as sowing was later, thus indicating that such methods have great performance in periods of longer days. In common, such methods used incident radiation data, and other variables are directly influenced by the angle of incidence of solar radiation. On the other hand, MAK uses global solar radiation data, and H uses photoperiod values. These results agree with studies in regions with similar latitudes in São Paulo State, Brazil, where higher underestimations were detected in the winter and spring (Vescove & Turco, 2005; Caporusso & Rolim, 2015).

The BL method had the lowest MBE values, ranging from 0.08 to 0.21 mm day⁻¹, differing from all other methods for sowings on Oct 21 and Nov 01, slightly tending to underestimations. On Nov 21, the BL method slightly tended to present overestimations and statistical similarities to the method PT. The method TP, previously pointed out with low accuracy, differed from all other methods, showing higher overestimations in all sowing dates, with mean deviations between 1.35 and 1.40 mm day⁻¹.

Figure 1. Mean bias error (MBE) for daily reference evapotranspiration calculated by the alternative methods Makkink (MAK), Hamom (H), Benevides-Lopez (BL), Priestley-Taylor (PT), and Tanner-Pelton (TP) in relation to the standard Penman-Monteith method, with sowing dates on Oct 10 (A), Nov 01 (B) and Nov 21 (C) in the 2013/2014 crop season in Londrina, PR, Brazil.



In general, PT had the greatest performance for daily ETo estimation, with high precision and accuracy in all sowing dates, in agreement with the results obtained by Silva et al. (2017). Except for the method BL on Nov. 21, PT differed from the other methods, receiving “great” classification. MAK was classified as “very good”, underestimating ETo values in the study period. The method BL was classified as “good”, with low precision of estimation as shown by the lowest R² values and must be avoided or used with caution (Silva et al., 2017).

10-day Period Performance

In the 10-day period scale, the nine alternative methods for estimating ETo and ETa in irrigated and non-irrigated environments were analyzed. The results of their performance (Table 3) indicate that the method THC showed the best accuracy (b) in all sowing dates (0.97; 1.00; 1.03), with satisfactory R² (0.78; 0.94; 0.95) and d (0.75; 0.87; 0.88), receiving a “very good” classification according to confidence statistical indices for sowing on Oct 10 (r = 1.0) and “great” for sowings, on Nov 01 (r = 1.0) and 21 (r = 0.97).

Comparing all sowing dates, Oct 10 showed the lowest

Table 3. Statistical performance of methods proposed for 10-day period ETo estimation in relation to the standard Penman–Monteith method, considering accuracy (b), precision (R²), agreement (d), confidence (c), and correlation (r). Sowing dates were on Oct 10, Nov 01 and Nov 21 in the 2013/2014 crop season in Londrina, PR, Brazil. The methods were: Priestley–Taylor (PT), Makkink (MAK), Hamon (H), Tanner–Pelton (TP), Benevides–Lopez (BL), Thornthwaite (TH), Thornthwaite–Camargo (THC), Camargo (CAM), and Hargreaves–Samani (HS).

Sowings	Coefficients	PT	MAK	H	TP	BL	TH	THC	CAM	HS
Oct 10	b	1.05	0.80	-	1.30	0.97	0.87	0.97	-	1.15
	R ²	0.47	0.77	-	0.32	0.54	0.31	0.78	-	0.47
	d	0.61	0.39	-	0.31	0.60	0.57	0.75	-	0.45
	c	0.68	0.58	-	0.39	0.60	0.41	0.83	-	0.66
	r	0.99	0.96	-	0.98	0.99	0.94	1.00	-	0.99
Nov 01	b	1.09	0.82	0.87	1.34	0.97	0.93	1.01	0.93	1.19
	R ²	0.94	0.97	0.86	0.93	0.83	0.84	0.94	0.84	0.93
	d	0.80	0.62	0.71	0.53	0.79	0.80	0.87	0.77	0.67
	c	0.93	0.88	0.85	0.76	0.87	0.87	0.96	0.87	0.87
	r	0.99	0.97	0.98	0.97	0.99	0.97	1.00	0.98	0.98
Nov 21	b	1.06	0.79	0.87	1.29	1.05	0.96	1.03	0.92	1.19
	R ²	0.93	0.96	0.90	0.90	0.88	0.91	0.95	0.85	0.93
	d	0.85	0.69	0.80	0.64	0.83	0.87	0.88	0.81	0.72
	c	0.95	0.89	0.91	0.83	0.90	0.94	0.97	0.92	0.91
	r	0.98	0.97	0.99	0.93	0.97	0.97	0.97	0.97	0.93

R² values for all ETo estimation methods. According to the statistical analysis of MBE for this sowing date (Table 4), the method THC slightly tended to underestimate values, presenting the lowest mean deviation (1.15 mm 10-day period⁻¹), with no differences regarding other methods that also showed underestimations (TH, CAM and BL). THC also did not differ from PT, which tended to overestimate values (2.68 mm 10-day period⁻¹). Similar results were obtained by Farias et al. (2020) when analyzing contrasts between dry and rainy seasons and describe that the similarity between the methods occurs because they use only variables of temperature and solar irradiation in their equations.

The methods PT and HS were similar, neither precise (R² = 0.47; 0.47) nor exact (d = 0.61; 0.45), despite high correlation with Penman–Monteith (r = 0.99) and accuracy (b = 1.05; 1.15). The two methods were classified as “good” (c = 0.68; 0.66) and overestimated values in all sowing dates. These results corroborate those of several authors in different regions of Brazil (Silva et al. 2017; Farias et al. 2020; Oliveira et al. 2020). The method TP presented the highest overestimation (MBE = 14.04 mm 10-day period⁻¹), classified as “awful”, being statistically similar to the method HS.

Also regarding sowing on Oct 10, the method MAK tended to underestimate values (b = 0.7963), with regular precision (R² = 0.7677) and low agreement (d = 0.39), despite higher correlation with the standard method (r = 0.96), thus classified as “regular” (c = 0.58). This method was not statistically different from H and CAM, classified as “awful”, and from TH, classified as “bad”, on such scale and sowing date. These results corroborate those obtained by Silva et al. (2017) and Farias et al. (2020).

On the sowing dates Nov. 01 and 21, all methods showed high correlation (r between 0.93 and 1) and higher precision compared to the previous sowing date (R² between 0.8342 and 0.9651) in the 10-day period scale. The THC method presented the greatest performance, with high accuracy (b = 1.0057; 1.0322), precision (R² = 0.9414; 0.9524) and agreement (d = 0.77; 0.81), being classified as “great” (c = 0.87; 0.92). According to mean deviations, the method THC was statistically different from MAK, TP and HS (Nov. 21).

Actual Yield (Ya) Estimations and Yield Deviations

ETo values of each method in the 10-day period scale were used to calculate water balances for soybean, according to phenological stages and sowing dates. After obtaining ETa values under irrigated and non-irrigated environments, we calculated 10-day period MBE values, which met the assumptions of the analysis of variance and were submitted to the Tukey test (p ≤ 0.05).

Under non-irrigated conditions, all methods showed similar results on the sowing dates Oct 10 and Nov 01. On Nov 21, the method MAK presented the highest underestimations and significantly differed from HS and TP, which led to the highest overestimations, with no statistical differences between them. The lowest deviations were obtained by the methods THC (Oct 10; 0.07 mm 10-day period⁻¹), CAM (Nov 01; 0.2 mm 10-day period⁻¹) and TH (Nov 21; 0.28 mm 10-day period⁻¹). These methods did not present statistical differences in the 10-day period scale regardless of the sowing date.

In the irrigated environment, the least significant difference (LSD) decreased in all sowing dates. The methods

over- or underestimating values in non-irrigated environment not only maintained their positions but also improved their performance when submitted to irrigation. In all sowing dates, the method MAK presented significant differences in relation to THC (except on Nov 01), PT, HS, and TP. The lowest deviations were detected in the methods CAM (Oct 10 and Nov 21) and THC (Nov 01), which did not present significant differences for any sowing date. The methods THC, PT, HS, and TP, in ascending order, overestimated values and were not statistically different in all sowing dates.

The 10-day period ETo values of each method were used in water balances for soybean in irrigated and non-irrigated environments, thus obtaining ETa for all sowing dates in the 2013/14 crop season in Londrina, PR, Brazil. ETa values were used to calculate Ya estimations as a function of water deficit. Theoretical potential yields were higher in earlier sowing dates, estimated by the Agro-Ecological Zone model, which considers ideal conditions for crop development (Figure 2 and 3).

The estimated Ym values were 4,689 kg ha⁻¹ for sowing on Oct 10; 4,451 kg ha⁻¹ for Nov 01; and 4,354 kg ha⁻¹ for Nov 21. Ya was obtained based on penalizing the Ym exclusively estimated by water deficit during the crop cycle. When ETa obtained from the standard Penman–Monteith method was used, estimated Ya values were 3,357 kg ha⁻¹ (non-irrigated) and 4,184 kg ha⁻¹ (irrigated) for sowing on Oct 10; 3,229 kg ha⁻¹ (non-irrigated) and 4,085 kg ha⁻¹ (irrigated) on Nov 01; and 3,333 kg ha⁻¹ (non-irrigated) and

3,906 kg ha⁻¹ (irrigated) on Nov 21.

The deviations between Ym and Ya estimations indicate theoretical losses regarding water availability. Such deviations were 28.4% (non-irrigated) and 10.7% (irrigated) for sowing on Oct 10, 27.4% (non-irrigated) and 8.2% (irrigated) on Nov 01, and 23.4% (non-irrigated) and 10.2% (irrigated) on Nov 21. When using the method of the Agroecological Zone in their studies, Assad et al. (2007) and Santos et al. (2011) observed greater losses of use due to water restrictions.

The field-obtained mean actual yields for the cultivar BRS-284 were 3,164 kg ha⁻¹ (non-irrigated) and 4,072 kg ha⁻¹ (irrigated) for sowing on Oct 10. Sowing performed on Nov 01 resulted in 2,728 kg ha⁻¹ (non-irrigated) and 2,945 kg ha⁻¹ (irrigated), while sowing on Nov 21 resulted in 1,447 kg ha⁻¹ (non-irrigated) and 3,102 kg ha⁻¹ (irrigated).

Maximum theoretical yields were lower in later sowings, corroborating the field-obtained real data, also observed by Crusiol et al. (2017), with increased losses in irrigated and non-irrigated environments. The latest sowing (Nov 21) resulted in large actual yield losses, which were larger than those resulting from water deficit. This fact can be due to the occurrence of pests and diseases reaching critical soybean phenological phases.

Yield losses can be estimated through the deviation between the actual yield and Ym calculated through the proposed method, according to some parameters and specific sowing dates. The deviations are not only related to water requirements during the crop cycle but also to other factors

Figure 2. Actual yield (Ya) from 10 methods for estimating 10-day period reference evapotranspiration, real yield (Yr) in non-irrigated environment and yield deviations in relation to the maximum yield (Ym), with sowing dates on Oct 10, Nov 01 and Nov 21 in the 2013/2014 crop season in Londrina, PR, Brazil.

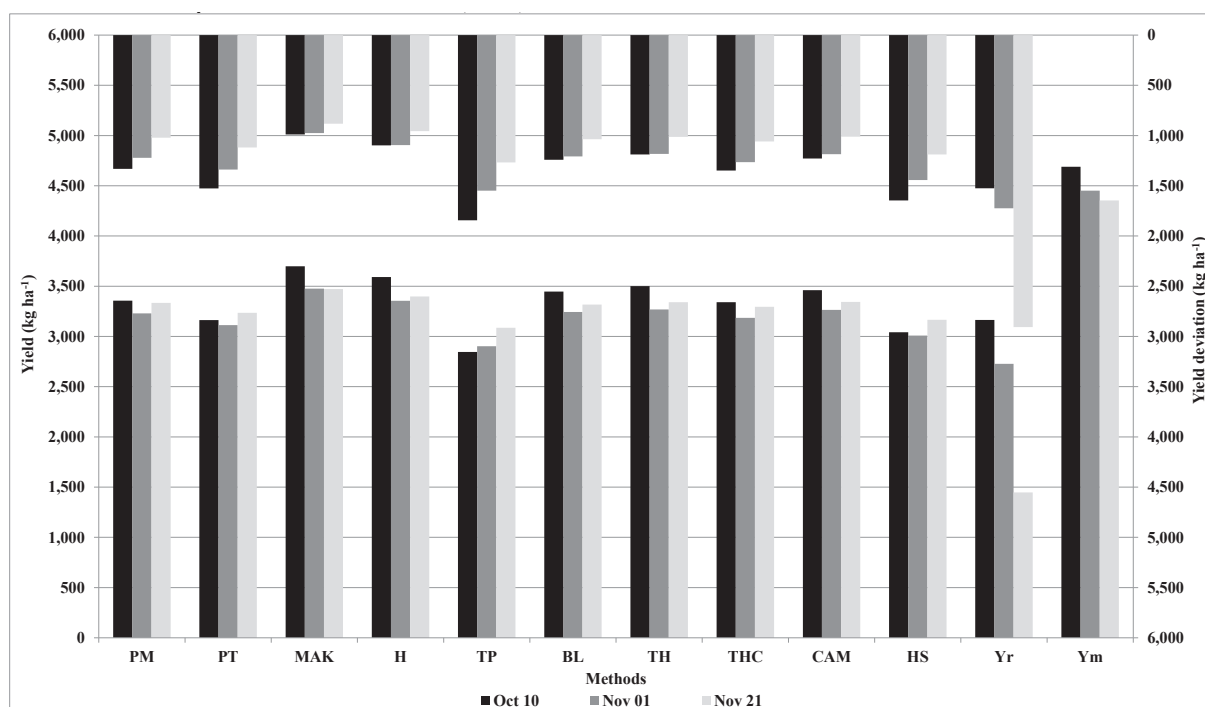
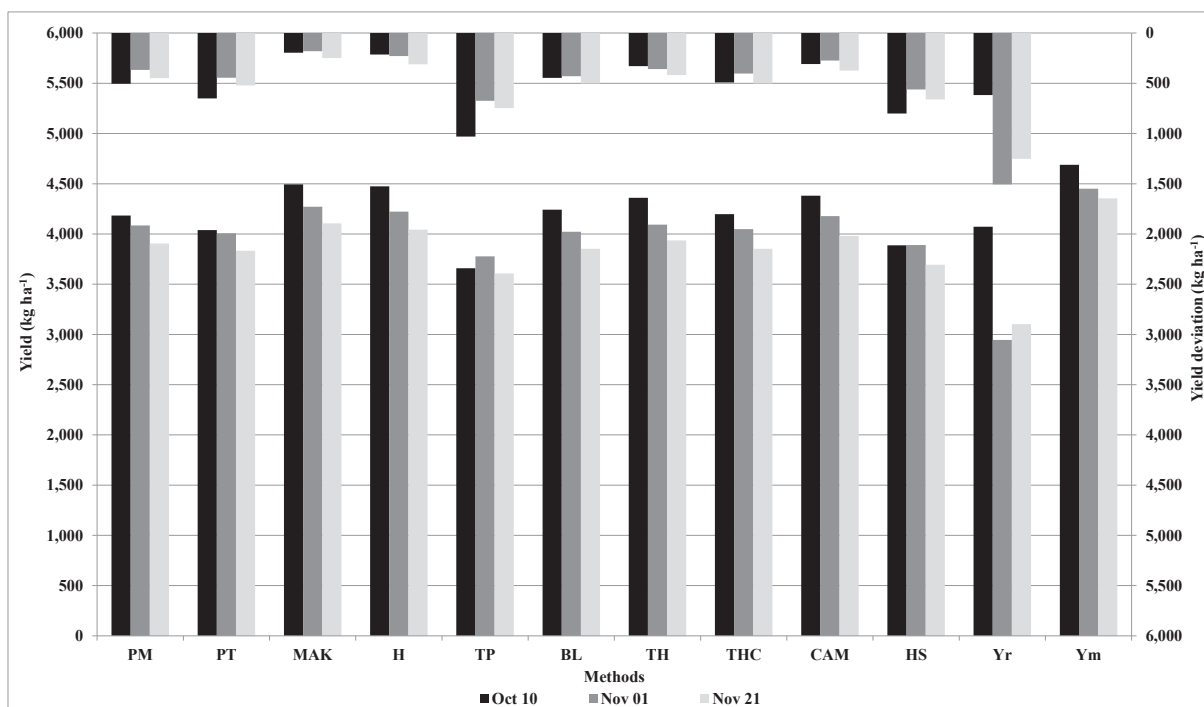


Figure 3. Actual yield (Y_a) from 10 methods for estimating 10-day period reference evapotranspiration, real yield (Y_r) in irrigated environment and yield deviations in relation to the maximum yield (Y_m), with sowing dates on Oct 10, Nov 01 and Nov 21 in the 2013/2014 crop season in Londrina, PR, Brazil.



not considered in the model (Assad et al., 2007), such as the occurrence of pests and diseases and crop management. Under non-irrigated conditions, the deviations between real and estimated potential yields were 32.5% (Oct 10), 38.7% (Nov 01) and 66.7% (Nov 21). Such deviations were lower in irrigated environment, with 13.1% (Oct 10), 33.9% (Nov 01) and 28.7% (Nov 21).

Since yield loss was estimated at 32.5% in non-irrigated environment on Oct 10 sowing, and the water deficit-induced deviation between maximum and actual yields was 28.4%, we can infer that 4.1% of yield loss were due to other not-modeled factors. Similarly, yield loss was 38.7% for sowing on Nov 01, 27.4% of which were due to water deficit and 11.3% resulting from other factors. Furthermore, on Nov 21 sowing, estimated yield loss was 66.7%, 23.4% of which were due to water deficit and 43.3% resulting from other factors not quantified by the method. As discussed by Assad et al. (2007), yield losses intensify in dry periods, with an increasingly pronounced gap between the estimate of a proposed model and the real value observed in the field.

Under irrigated conditions, on the Oct 10 sowing, the estimated yield loss was 13.1%, 10.7% of which were due to water deficit and 2.14% resulting from other factors. On Nov 01, the estimated yield loss was 33.9%, 8.2% of which were due to water deficit and 25.7% due to other factors. On Nov 21, losses were estimated at 28.7%, 10.2% of which were due to water requirements and 18.5% resulting from other factors.

In non-irrigated environment, methods did not present significant differences for E_{Ta} on Oct 10 and Nov 01 sowings, but they were different regarding E_{To} (Table 4). Y_a values estimated through the THC method were the most similar to those of PM (standard) on such dates, with reduction of 0.46% (-16 kg ha^{-1}) and 1.35% (-43 kg ha^{-1}), respectively.

At these first two sowings, the method THC was statistically similar to BL, CAM, TH, and PT, and similar to the H method only on Nov 01. When used in yield estimations (Figure 2), the method BL was superior to the standard at 2.7% (Oct 10) and 0.43% (Nov 01), overestimating Y_a at 90 kg ha^{-1} and 43 kg ha^{-1} , respectively. The method CAM also overestimated at 103 kg ha^{-1} (+3.10%) and 36 kg ha^{-1} (+1.11%) on the first and second sowing dates, respectively.

Similarly, the method TH overestimated 144 kg ha^{-1} (+4.30%) and 39 kg ha^{-1} (+1.21%) at these same dates, respectively, and the method H on Nov 01 (+3.91%), equivalent to 126 kg ha^{-1} . On the other hand, the method PT underestimated Y_a obtained through the standard method, showing differences of 194 kg ha^{-1} (-5.78%) and 116 kg ha^{-1} (-3.61%) on such dates. The methods H (Oct 10; +7%; +234 kg ha^{-1}) and MAK (+10.20%; +342 kg ha^{-1}) showed similar results, but differed from those of HS (-9.37% ; -315 kg ha^{-1}) and TP (-15.24% ; -512 kg ha^{-1}); the last two methods were similar to each other.

For the latest sowing (Nov 21) in non-irrigated environment, MBE values obtained by the method H were diffe-

Table 4. Tukey test ($p \leq 0.05$) and least significant difference (LSD) for the mean bias error (MBE), in 10-day period scale, regarding reference evapotranspiration (ET_o) and actual crop evapotranspiration (ET_a) of soybean under irrigated and non-irrigated environments, through the proposed methods in relation to the standard Penman–Monteith method, with sowing dates on Oct 10, Nov 01 and Nov 21 in the 2013/2014 crop season in Londrina, PR, Brazil.

	ET _o			ET _a (non-irrigated)			ET _a (irrigated)		
	Oct 10	Nov 01	Nov 21	Oct 10	Nov 01	Nov 21	Oct 10	Nov 01	Nov 21
MAK	-9.17a	-9.63a	-9.92a	-2.85a	-2.75a	-3.78a	-5.60a	-5.82a	-5.60a
H	-8.03ab	-6.80ab	-5.44ab	-2.21a	-1.40a	-1.07ab	-2.16ab	-3.74ab	-2.16ab
TH	-5.72abc	-3.74ab	-1.16bc	-1.35a	-0.66a	0.28abc	-0.17abc	-2.21abc	-0.17abc
CAM	-5.13abc	-3.46ab	-2.05abc	-0.77a	-0.20a	0.68abc	0.08abc	-1.43abc	0.08abc
BL	-1.65bcd	-1.22bc	1.98bc	-0.44a	-0.43a	0.50abc	0.42abc	-0.90abc	0.42abc
THC	-1.15cd	0.26bc	2.23bc	0.07a	0.27a	1.40abc	1.37bcd	0.25abcd	1.37bcd
PT	2.68de	4.54cd	3.80cd	1.02a	1.38a	1.74abc	2.09bcd	1.89bcd	2.09bcd
HS	7.34ef	9.80de	10.82de	1.99a	2.80a	4.87bc	5.50cd	4.51cd	5.50cd
TP	14.04f	17.42e	15.78e	3.20a	4.00a	5.68c	6.78d	6.22d	6.78d
LSD	6.76	7.92	8.43	8.19	7.11	6.55	6.33	6.77	6.33

rent from those of TP, while values obtained by the method MAK were different from those of HS and TP; these last two methods were not different from each other. The methods most similar to PM (standard) with no significant differences were TH (+0.21%; +7 kg ha⁻¹), CAM (+0.30%; +10 kg ha⁻¹), BL (-0.46%; -15 kg ha⁻¹), THC (-1.16%; -39 kg ha⁻¹), H (+1.95%; +65 kg ha⁻¹), and PT (-2.95%; -98 kg ha⁻¹). The methods showing statistical differences were MAK (+4.13%; 138 kg ha⁻¹), HS (-5.02%; -167 kg ha⁻¹), and TP (-7.4%; -246 kg ha⁻¹).

In irrigated environment, regardless of the sowing date, the methods presented the same statistical pattern, i.e. sowings on Oct 10 and Nov 21 led to the same MBE values for ET_a, with very similar LSD values. The only difference was detected in the Nov 01 sowing, in which THC differ from other dates (Table 4).

In such an environment, the THC method showed the most similar estimated Ya to those of PM (standard) on Oct 10 sowing, with increase of 0.32% (+13 kg ha⁻¹). On such date, only the MAK method was different from THC, estimating Ya superior to that of PM at 7.4% (+310 kg ha⁻¹). Sowings on Nov 01 and 21 differed at 0.20% (+8 kg ha⁻¹) and 0.79% (+30 kg ha⁻¹), respectively, in relation to the standard method. TP was the only method statistically different from TH, underestimating Ya at 7.52% (-308 kg ha⁻¹) on Nov 01, and 7.62% (-298 kg ha⁻¹) on Nov 21.

ET_a showed the same MBE values on Oct 10 and Nov 21 sowings under irrigated conditions (Table 4), but different Ya estimations. The BL method overestimated at 1.40% (+58 kg ha⁻¹) for Oct 10 and underestimated at 1.37% (-54 kg ha⁻¹) for Nov 21. TH overestimated at 4.20% (+176 kg ha⁻¹) and 0.78% (+30 kg ha⁻¹); CAM at 4.72% (+197 kg ha⁻¹) and 1.93% (+75 kg ha⁻¹); H at 6.96% (+291 kg ha⁻¹) and 3.50% (+136 kg ha⁻¹), on such dates, respectively. Similarly, underestimations were detected in the methods PT at 3.47% (-145 kg ha⁻¹) and 1.86% (-73 kg ha⁻¹); HS at 7.08%

(-296 kg ha⁻¹) and 5.43% (-212 kg ha⁻¹); and TP at 12.56% (-526 kg ha⁻¹) and 7.62% (-298 kg ha⁻¹).

Water deficit-induced soybean yield losses estimated by the models in non-irrigated environment were 26.4% on average. Under irrigated conditions, such values were 9.7% in function of failures in irrigation management of experimental plots.

Conclusions

Priestley–Taylor was the best alternative method to Penman–Monteith for daily reference evapotranspiration estimations. At 10-day period scale, Thornthwaite–Camargo was the best alternative method in all sowing dates, with confidence statistical indices “very good” and “great” in later sowings. For calculating Ya, the best alternative methods to estimate 10-day period evapotranspiration were Thornthwaite–Camargo, Benevides–Lopez, Camargo, and Thornthwaite, which showed the lowest deviations compared to the method recommended by FAO.

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Author contributions

R. C. FERREIRA, R. N. R. SIBALDELLI and J. R. B. FARIAS designed the study, conducted the experiments, analyzed the data, performed the analysis and wrote the manuscript. O. J. G. ABI-SAAB, M. A. de A. e SILVA analyzed

the methodology and data, contributed to the analysis of results and statistical analysis.

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Avaliação de métodos alternativos para cálculos de evapotranspiração e seus impactos nas estimativas de produtividade de soja

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RESUMO

Apesar de diversos estudos comparativos entre métodos para estimativa de evapotranspiração potencial (ET_o), não foram encontrados relatos do uso e avaliação de tais métodos em modelagem agrometeorológica, principalmente no que se refere ao confronto dos resultados estimados obtidos na modelagem com dados reais de produção obtidos experimentalmente em campo. O presente estudo avaliou nove métodos alternativos para cálculo de ET_o utilizados para estimativas de produtividade da soja, associadas às produtividades reais obtidas em campo irrigado e não irrigado, em três épocas de semeadura na safra 2013/2014 no Sul do Brasil. Todos os métodos foram avaliados em relação ao método padrão de Penman-Monteith. Os desempenhos foram medidos por meio de análises de regressão e coeficientes estatísticos, submetidos ao teste de Tukey. Os valores de ET_o obtidos pelos métodos alternativos foram utilizados em cálculos de balanços hídricos para cultura da soja, considerando ambientes irrigados e não irrigados. As produtividades potenciais teóricas e reais foram maiores em plantios mais tardios. O método de Priestley-Taylor foi o melhor para estimar a ET_o diária de forma alternativa ao recomendado pela FAO (Penman-Monteith). Por outro lado, o método alternativo de Thornthwaite-Camargo foi o melhor para estimar em escalas decendiais, em todas as épocas de semeadura. Além disso, os métodos de Thornthwaite-Camargo, Benevides-Lopez, Camargo e Thornthwaite apresentaram os menores desvios para estimar ET_o em escalas decendiais para cálculos dos rendimentos reais (Y_a).

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