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Calibration of reference evapotranspiration models in Pará

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ABSTRACT. The use of empirical agrometeorological models that can be adjusted to the climatic conditions of different regions has become increasingly necessary to improve water management in grain-producing municipalities. The aim of this work is to examine the correlation between various reference evapotranspiration (ETo) estimation methods and the standard FAO 56 Penman-Monteith method, as well as to determine correction factors, when necessary, for crop-producing municipalities in the northeast of Pará, during both the rainy and dry seasons. We compared simpler methods of ETo estimation to the FAO 56 Penman-Monteith method. For this purpose, meteorological data from Tracuateua, Bragança, Capitão Poço and Castanhal, provided by the National Institute of Meteorology (INMET), were used. The calibration of equations was performed through linear regression. The accuracy of different estimation methods was examined. The Turc, FAO 24 Blaney-Criddle and regression methods presented the best results for all statistical criteria; the Priestley-Taylor, Makkink and FAO 24 Radiation methods presented excellent results after calibration. The methods of Camargo and Hargreaves-Samani produced the worst results for all the criteria.

Keywords: Penman-Monteith FAO 56; climate monitoring; water requirements.

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Introduction

The sowing of some crops in the North Region of Brazil is normally restricted to the first half of the year, the rainy season; if a second or third planting were adopted during the dry season, the yield could be much higher. This would require irrigation in order to partially or completely meet water needs, based on the rainfall regime of the region. In the state of Pará, for example, a daily or even more frequent irrigation schedule could be adopted to allow an increase in crop production during these periods; such changes would obviously respect the enormous difficulties encountered in the state, ranging from financial problems to the absence of specialized technical support (Souza, Pantoja, Amaral, & Neto, 2012)

In the state of Pará, the cowpea productivity stands out from that in other states in this region of Brazil, where cowpea is one of the most widely cultivated crops. In recent years, the region has highlighted the strong incorporation of technology into the production system, with the objective of reducing risks and improving production planning (Rebello, Costa, & Figueiró, 2011); such developments have thus allowed the use of models to become an excellent planning tool. Silva, Silva, Bezerra, and Almeida (2016) concluded that the productivity of irrigated cowpea was 34.4% higher than that of rainfed cowpea in Apodi, Rio Grande do Norte, and irrigated cowpea is economically viable, with a net income 37% higher than that of rainfed cowpea.

Irrigation management, for example, requires precise information on the water consumption of the plants and on the storage of soil water, and the meteorological water balance has often been adopted as a viable alternative when limited meteorological data are available (Carvalho, Rocha, Bonomo, & Souza, 2015). On the other hand, the simplifications adopted in the method and the consideration of the available water capacity as invariable (Pereira, 2005) make this approach inefficient due to the substantial lack of more accurate data on crop evapotranspiration.

Crop evapotranspiration can be calculated if both the reference evapotranspiration and crop coefficient are known; thus, the control of irrigation can be rationally performed, based on the actual needs of the crop. The FAO 56 Penman-Monteith method is still the most widely used method for the estimation of ETo (Chagas et al., 2013). On the other hand, the use of other indirect methods is justified by the need for estimates that require a smaller amount of meteorological information, especially in estimates intended for use by producers. Differences in estimations of ETo by empirical methods can be minimized by the adoption of correction factors that bring the results closer to estimations of ETo obtained by the FAO 56 Penman-Monteith method.

Oliveira et al. (2015) concluded that empirical methods show high reliability when calibrated with correction factors obtained by comparison with the results of the FAO 56 Penman-Monteith method. Many studies have been carried out to examine the performance of different methods in estimating ETo in comparison with the FAO 56 Penman-Monteith method (Carvalho et al., 2015; Chagas et al., 2013; Lacerda & Turco, 2015; Silva, Montenegro, Santos, & Santos, 2014); however, only a few such studies have been performed in geopolitical divisions of the Amazon region, such as Roraima (Araújo, Conceição, & Venancio, 2012) and the North Region of Brazil (Sanches, Ximenes, Coradi, Roque, & Cunha, 2015), and they do not consider seasonality.

The abovementioned works show that methods other than the FAO 56 Penman-Monteith method may be used with good reliability. Therefore, this work aims to compare different methods for estimating ETo commonly used in the literature to the standard FAO Penman-Monteith method, as well as to find correction factors, when necessary, to be used for a precise estimate of ETo in the region, during both the rainy and dry seasons.

Material and methods

The study was conducted for cowpea-producing municipalities in the northeast of Pará: Tracuateua, the largest producer of cowpea in the northeast of Pará (2,240 t year^{-1}); Bragança, the third-largest producer of cowpea in the northeast of Pará (2,000 t year^{-1}); Capitão Poço, the fourth-largest producer of cowpea in the northeast of Pará (1,400 t y^{-1}); and Castanhal (450 t year^{-1}) (SAGRI, 2015).

Meteorological data recorded by automated and conventional weather stations and provided by the National Institute of Meteorology (INMET) were used. The stations were installed in each of the abovementioned municipalities, and they recorded data at different time intervals based on their installation dates (Table 1). Although in some of the cities used, the dataset is not long enough, the high demand for studies of this nature has forced some researchers to develop work with even smaller data series due to the unavailability of climatic data (Carvalho et al., 2015; Tanaka et al., 2016).

Table 1. Automated and conventional weather stations used in this work.

ID	Weather station	Latitude	Longitude	Altitude (m)	Period (month/year)
81685	Bragança	-1.047258°	-46.785790° W	41	Mar./2008 – Dec./2015
81684	Capitão Poço	-1.73472°	-47.0575° W	79	April/2011 – Dec./2015
82145	Tracuateua	-1.066667°	-46.9° W	36	Jan./2000 – Dec./2015
81682	Castanhal	-1.300875°	- 47.947967° W	47	Jan./2003 – Dec./2015

The following data were used in this research: average, maximum, and minimum daily air temperature (°C); average air relative humidity (%); wind speed (m s^{-1}); and solar radiation (MJ m^{-2} day^{-1}), in municipalities with automated weather stations. In Tracuateua, which has a conventional weather station, the global radiation was calculated from sunshine hours. Data were tabulated in electronical sheets, and a consistency analysis was performed.

The ETo used for the evaluation of the simplified models was obtained by the FAO 56 Penman-Monteith method (Equation 2), i.e., parameterized according to the FAO irrigation and drainage paper No. 56 (Allen, Pereira, Howell, & Jensen, 2011) using air temperature and relative humidity. The other variables were obtained according to the recommendations of Allen et al. (2011).

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

where: ETo - reference evapotranspiration (mm day^{-1}); R_n - net radiation (MJ m^{-2} day^{-1}); G - soil heat flux (MJ m^{-2} day^{-1}); T_{air} - air average temperature throughout the day (°C); U_2 - wind velocity (m s^{-1}); (e_s-e_a) - vapor pressure deficit (kPa); Δ - slope of the vapor saturation pressure as a function of air temperature (kPa °C^{-1}); $\gamma = c_p P(0.622\lambda)^{-1}$ - psychrometric constant (kPa °C^{-1}); the constant 0.408 corresponds to λ^{-1}, where: λ is the latent heat of vaporization of water (2.45 Mj kg^{-1}); and the constant 900 is a conversion factor for daily data.

ETo was estimated by other methods with higher potential for daily use, by using a computer program according to the equations below:

Blaney-Criddle-FAO 24 (Equation 2) (Doorenbos & Pruitt, 1977).

$$\text{ETo} = a + bf \quad (2)$$

where: a - intercept of the linear equation between ET_0 and f (mm day^{-1}); b - slope of the linear equation between ET_0 and f; $f = p(0.46T_{air} + 8.13)$ is a factor of consumptive usage; p - percentage of actual sunshine hours in relation to the annual total, for a given month and latitude; and T_{air} = monthly daily average air temperature (°C).

$$a = 0.0043RH_{min} - \frac{n}{N} - 1.41 \quad (3)$$

$$b = a_0 + a_1 + RH_{min} + a_2\frac{n}{N} + a_3u_d + a_4RH_{min}\frac{n}{N} + a_5 \quad (4)$$

where: a_0, a_1, a_2, a_3, a_4, and a_5 correspond to 0.8197, -0.0040922, 1.0705, 0.065649, -0.0059684, and 0.0005967, respectively; RH_{min} - daily relative humidity (%); n - sunshine hours (h); N - maximum available daylight hours (h); and U_d - diurnal wind speed (m s^{-1}).

Camargo (Equation 5) (Camargo & Camargo, 2000).

$$\text{ETo} = F \cdot R_o \cdot T_{air} \cdot ND \quad (5)$$

where: F - correction factor that depends on the local average monthly air temperature (F=0.01 for T= 23°C, F=0.0105 for T=24°C; F=0.011 for T= 25°C, F=0.0115 for T= 26°C, and F=0.012 for T > 26°C); ND – number of days in the period; and R_0 - extraterrestrial radiation (MJ m^{-2} day^{-1}).

Hargreaves-Samani (Equation 6) (Samani, 2000).

$$\text{ETo} = 0.0023R_o(T_{max} - T_{min})^{0.5} \cdot (T_{air} + 17.8) \quad (6)$$

where: T_{air} - average temperature (°C); T_{max} - maximum temperature (°C); and T_{min} - minimum temperature (°C).

Makkink (Equation 7) (Apud Pereira, Villa Nova, Sediyama, 1997).

$$\text{ETo} = 0.61 \times \frac{\Delta}{\Delta+\gamma} \times R_g - 0.12 \quad (7)$$

Priestley-Taylor (Equation 8) (Apud Pereira et al., 1997).

$$\text{ETo} = 1.26 \times \frac{\Delta}{\Delta+\gamma} \times (R_n - G) \quad (8)$$

Radiation-FAO 24 (Equation 9) (Doorenbos & Pruitt, 1977).

$$\text{ETo} = (a + b) \times \frac{\Delta}{\Delta+\gamma} \times R_g \quad (9)$$

where a = 0.3 mm d^{-1} - adjustment factor that depends on average air relative humidity (UR_m) and diurnal wind speed (U_d).

$$b = 1.066 - 0.0013UR_m + 0.045U_d - 0.0002UR_mU_d - 0.0000315UR_m^2 - 0.0011U_d^2 \quad (10)$$

Turc (Equation 11) (Apud Kashyap & Panda, 2001).

$$\text{ETo} = \frac{0.013T_{air}}{T_{air}+15}\left(23.9R_g + 50\right) \quad (11)$$

ETo was also estimated by a multiple regression equation as a function of solar radiation (R_g), vapor pressure deficit (VPD) and wind speed (U_2). Due to the great interest in verifying the relation of the input variables (Rg, VPD and wind speed) with the output variable (evapotranspiration), ETo was also estimated by a multiple regression function. The multiple regression model was generated by considering that a large part of the variation in the output variable (ETo) is explained by the input variables.

Global radiation (R_a) was estimated by the equation proposed by Angström and modified by Prescott whenever necessary, using the coefficients suggested by Glover and McCulloch, similarly to Silva et al. (2014).

$$R_g = \left(a + b\frac{n}{N}\right)R_o \quad (12)$$

where: R_g is the daily total solar radiation (MJ m^{-2} day^{-1}); n is the actual duration of sunshine (h day^{-1}); N is the maximum possible duration of sunshine or daylight hours (h day^{-1}); R_o is the extraterrestrial radiation, obtained according to the recommendations of Allen et al. (2011); a = 0.29 *cos*(latitude); and b = 0.52.

Comparisons were performed for two six-month periods of daily data with different characteristics: the first period (from January to June) is when most of the annual rain occurs, and the second one (from July to December) has higher evaporimetric demand.

The analysis of the performance of the models was performed by comparing ETo values obtained from the alternative methods with the ETo value calculated by FAO 56 Penman-Monteith, using the agreement index of Willmott et al. (1985) (d), the normalized root mean square error (NRMSE) and the standard error of estimate (SEE). The best models must have high values of d and small values of both NRMSE and the standard error of estimate (SEE), as d and the error variables indicate the accuracy and the error of the estimate, respectively.

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

$$SEE = \sqrt{\frac{\sum_{i=1}^{n}(P_i - O_i)^2}{n-1}} \quad (14)$$

where: O_i is the ETo estimated by the FAO 56 Penman-Monteith equation, P_i is the ETo estimated using other methods, $\bar{O}$ is the average of the observed data (P-M method) and n is the number of data points.

Estimations were also classified according to the performance index described by Camargo and Sentelhas (1997), which is the product of *r* (Pearson correlation coefficient) and *d*.

After calculations of ETo were performed, a regression analysis using a linear model was performed, in which the FAO 56 Penman-Monteith equation was compared to other methods by examining the equations generated by the comparison; this approach is similar to the methodology used by Oliveira et al. (2015) to compare various methods of estimation of ETo to the standard FAO 56 Penman-Monteith method. Correction factors were calculated only for equations showing good performance (i.e., performance index (*c*) ranging from 0.71 to 0.80) and acceptable squared errors ranging from 10 to 30%; then, the equations were compared to FAO 56 Penman-Monteith once again to examine the correction. Those methods with inadequate performance for the region were not calibrated, since corrections of such methods will not improve their efficiency. The best-performing methods with index (c) values higher than 0.85 were also not calibrated.

Results and discussion

The weather variables shown in Figure 1 are the ones with the greatest influence on the estimation of evapotranspiration, and they are essential for the FAO 56 Penman-Monteith method (Chang, 1971). The results clearly show the existence of two different seasons in all the municipalities: as seen, most of the rainfall and the highest measurements of air relative humidity occur from January to June, and the lowest ones occur from July to December.

The regression method (Equation 15) was adjusted to incorporate the effect of solar radiation, vapor pressure deficit and wind speed (input variables) on the reference evapotranspiration process (output variable). The results presented a high correlation (r = 0.99) and high coefficient of determination (R^2 = 0.99), with elevated statistical significance (F-test, $p < 0.05$).

$$\text{ETo} = 0.15R_g + 0.75VPD + 0.26U_2 + 0.24 \quad (15)$$

The Turc and FAO 24 Blaney-Criddle regression methods had the best accuracy, as shown in Figures 2 and 3. In other words, the intercept a and the slope b were close to 0 and 1, respectively. The good fit of the regression equation was already expected, since the equation was created for the climatic conditions of the studied region (R^2 = 0.99; r = 0.98). Additionally, such equations take variables of major importance for evapotranspiration into account (Chang, 1971).

The Hargreaves-Samani method overestimated evapotranspiration when it was lower than 5 mm day^{-1}. A possible explanation is that the high air relative humidity in humid regions reduces evapotranspiration once the air is close to saturation and that the methods based only on air temperature and solar irradiance tend to overestimate reference evapotranspiration for humid regions despite the high energy availability (Lemos

Filho, Mello, Faria, & Carvalho, 2010). Air relative humidity is a decisive factor in vapor pressure deficit, which is an indicator of air evaporative capacity.

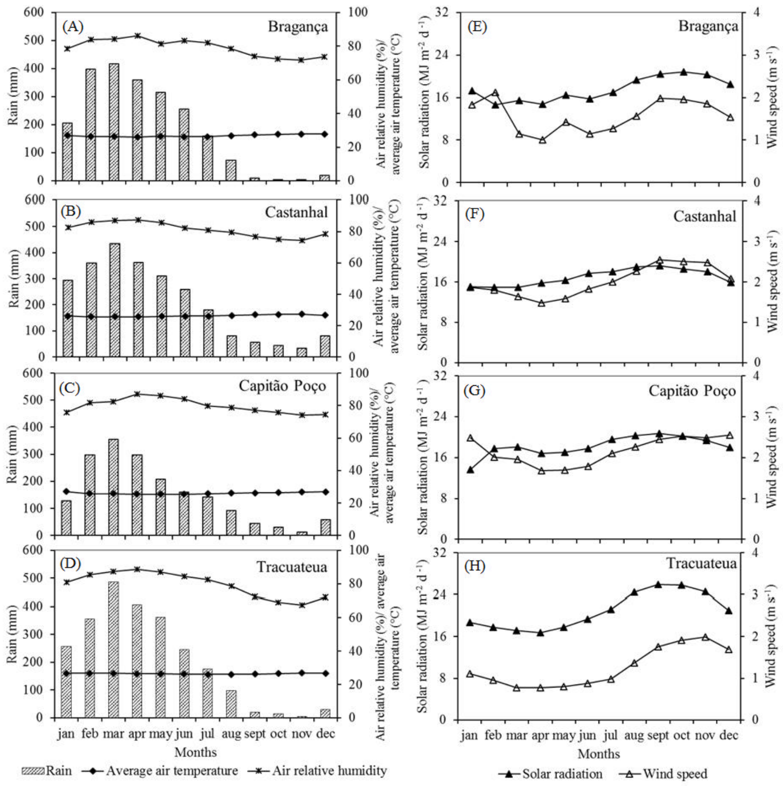

Figure 1. Monthly averages of meteorological variables. Air relative humidity (%), average air temperature (°C), solar radiation (MJ m^{-2} day^{-1}), wind speed (m s^{-1}) and rainfall (mm) in Tracuateua, Bragança, Capitão Poço, and Castanhal.

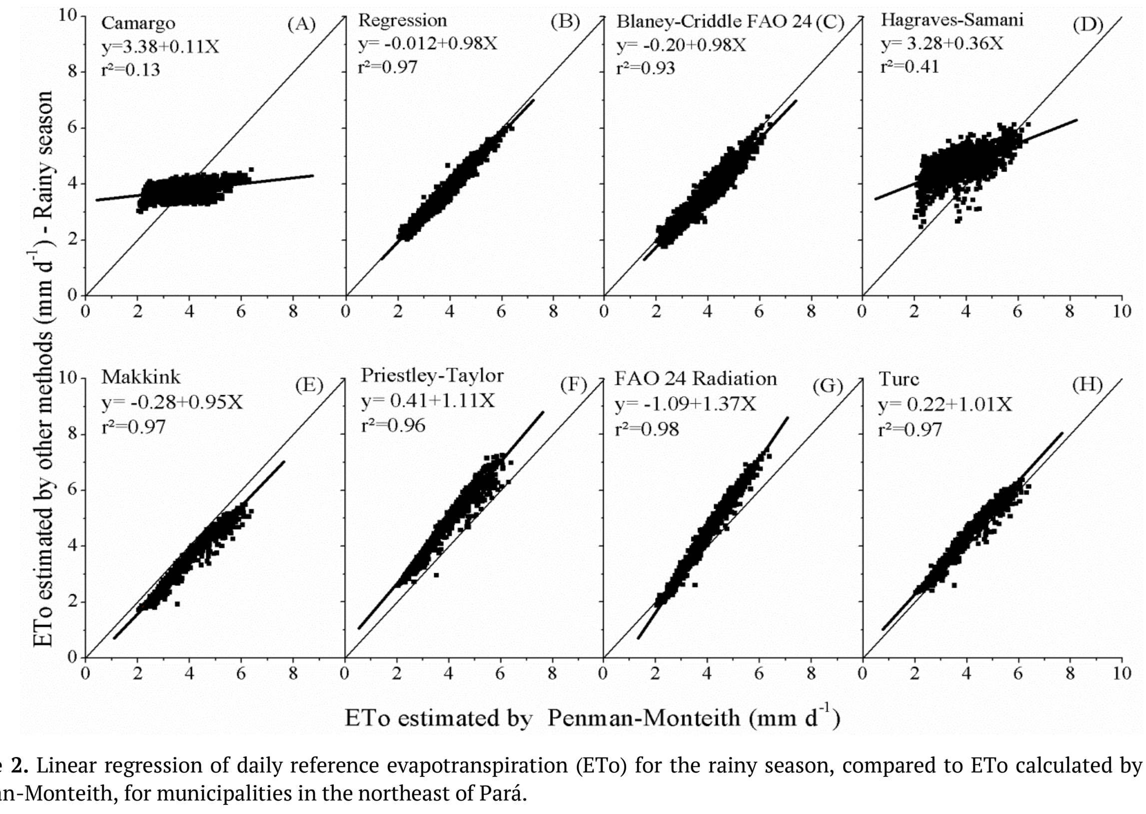

Figure 2. Linear regression of daily reference evapotranspiration (ETo) for the rainy season, compared to ETo calculated by FAO 56 Penman-Monteith, for municipalities in the northeast of Pará.

On the other hand, the Hargreaves-Samani method underestimated ETo calculated by Penman-Monteith FAO 56 when it was higher than 5 mm day^{-1} (Figure 2D and 3D) in both seasons. Elevated ETo is an indication of high atmospheric demand, which occurs when the air relative humidity is low and vapor pressure deficit is high and therefore controls ETo despite solar energy. The fact that the Hargreaves-Samani method does not take the evaporative power of the air into account may have caused the underestimation of reference evapotranspiration in this situation.

It is worthwhile to highlight that the Hargreaves-Samani method has low accuracy and precision (Table 2) but its r^2 is slightly improved from the rainy to the dry season (Figure 3D). Caporusso and Rolim (2015) also identified that the mean absolute error of this method increased from winter to summer at all analyzed time scales. These variations may be explained by the fact that the equation was fitted for the semiarid climate of California (Samani, 2000) and the small differences between maximum and minimum air temperature in the region, which influence the local humidity conditions (Samani, 2000).

Camargo's method overestimated reference evapotranspiration at values lower than 3 mm day^{-1} (Figure 2A); therefore, the method behaved similarly to the Hargreaves-Samani method and yielded even worse accuracy. The explanation for this behavior is probably the same as that given above, since this method also takes only air temperature and solar irradiance into account; furthermore, this method may have worse accuracy because it uses extraterrestrial radiation. Even though some authors claim the model shows better results on cloudy days (Borges Júnior, Anjos, Silva, Lima, & Andrade, 2012; Souza, Farias, Moreira, Gomes, & Junior, 2011) and during winter (Caporusso & Rolim, 2015), the model yielded very poor accuracy in all seasons.

The FAO 24 Radiation and Priestley-Taylor methods showed high r^2 values, which demonstrates a high precision of the estimation (Figure 2F-G). However, the adoption of r^2 as the only criterion to assess the fit of a model is not recommended, as both methods had good performance and good or acceptable precision (Table 2). Therefore, r^2 does not explain the type and magnitude of differences between the value estimated by the standard method and the values predicted by other methods.

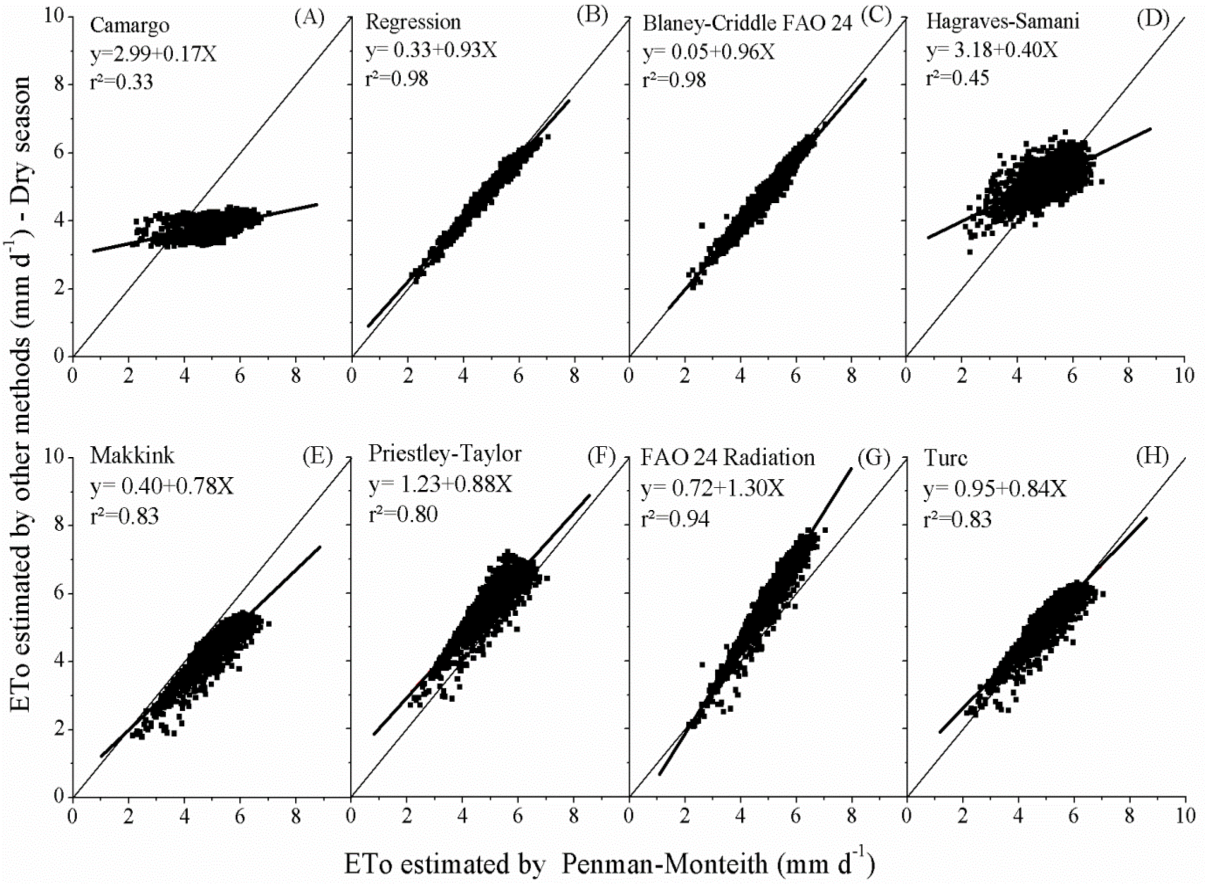

Figure 3. Regression equations of daily reference evapotranspiration (ETo) for the dry season, estimated by FAO 56 Penman-Monteith and compared to other methods, for different municipalities in the northeast of Pará.

Both methods (FAO 24 Radiation and Priestley-Taylor) overestimated ETo during both the rainy and dry seasons (Figures 2F-G and 3F-G). The method of Priestley-Taylor was developed to estimate evaporation from saturated surfaces in a non-saturated atmosphere, which are the normal conditions found in nature (Cavalcante Junior, Oliveira, Almeida, & Sobrinho, 2011). However, the Priestley-Taylor method was the best one for estimating the reference evapotranspiration in the municipality of Jaboticabal, São Paulo State, Brazil (Caporusso & Rolim, 2015).

Araújo, Reis Martins, Barbosa, and Rodrigues (2011) observed overestimations of ETo calculated by the FAO 24 Radiation method (in comparison to the FAO 56 Penman-Monteith method) in the southeast of Brazil by approximately 23.85% on a daily scale. Similar behavior was observed by Sanches et al. (2015) for the North Region of Brazil, where the original FAO 24 method had good performance and the calibrated FAO 24 method had very good performance.

The method of Makkink had lower precision during the driest season in the studied cities (Figures 2E and 3E). Cavalcante Jr. et al. (2011) observed a similar behavior in the semiarid climate of the Northeast Region of Brazil, since the equation was originally developed for the climate conditions of Wageningem, The Netherlands. In addition, the Makkink method is indicated for the estimation of evapotranspiration in grouped periods of 10 or 30 days (Camargo & Camargo, 2000).

Souza et al. (2011) concluded that methods developed for application over larger data periods can be applied in shorter intervals when the sky cover approaches the local climatic conditions of origin of the method. Furthermore, in a study in Jaboticabal, SP in the same period of the year (winter-spring), Caporusso and Rolim (2015) found similar mean absolute errors to that obtained in this work for Makkink method when applied on a daily scale (15 to 21%), as shown in Table 2.

On the other hand, the method of Turc showed an excellent fit during the rainy season and very good performance during the dry season, with excellent performance for all the statistical parameters used to assess the efficiency of the model in all the cities analyzed. This good fit and performance occurred because both methods (Penman-Monteith FAO 56 and Turc) are energetic, and methods that use solar irradiance show better performance than methods that use only air temperature (Kashyap & Panda, 2001).

Statistical parameters for the assessed methods are shown in Table 2 for both the rainy and dry seasons. The regression, Turc, and FAO 24 Blaney-Criddle methods had the best results according to all statistical parameters for all the cities, for both the rainy and dry seasons, in comparison to the standard method.

Table 2. Performance classification of different methods of estimation of ETo compared to the FAO 56 Penman-Monteith method, for cities in the northeast of Pará, during both the rainy and dry season.

			Rainy season			
Method	*d*	*r*	*c*	NRMSE (%)	SEE (mm day^{-1})	Classification
Camargo	0.42	0.36	0.16	22.82	1.18	Very poor
Regression	0.99	0.98	0.97	5.06	0.19	Excellent
FAO 24 Blaney-Criddle	0.96	0.96	0.92	10.12	0.38	Excellent
Hargreaves-Samani	0.61	0.64	0.39	30.16	1.14	Very poor
Makkink	0.93	0.98	0.92	12.81	0.48	Excellent
Priestley-Taylor	0.81	0.98	0.79	22.84	0.86	Good
FAO 24 Radiation	0.95	0.99	0.94	13.02	0.49	Excellent
Turc	0.97	0.98	0.95	8.66	0.33	Excellent
			Dry season			
Method	*d*	*r*	*c*	NRMSE (%)	SEE (mm day^{-1})	Classification
Camargo	0.48	0.57	0.27	26.04	1.34	Very poor
Regression	0.99	0.99	0.98	2.74	0.13	Excellent
FAO 24 Blaney-Criddle	0.98	0.98	0.96	4.00	0.20	Excellent
Hargreaves-Samani	0.75	0.67	0.50	11.40	0.58	Tolerable
Makkink	0.80	0.91	0.72	14.22	0.73	Good
Priestley-Taylor	0.83	0.89	0.74	13.23	0.68	Good
FAO 24 Radiation	0.92	0.97	0.80	15.82	0.81	Good
Turc	0.95	0.91	0.86	6.44	0.33	Very good

d – Willmott index, r – Pearson correlation coefficient, c – performance index, NRMSE - normalized root mean square error, SEE - standard error of estimate.

Blaney-Criddle FAO 24 is a more practical method, as it requires only air temperature and some information about the climate; therefore, this method is appropriate for monthly estimations of ETo. It is also the most laborious method based on temperature in this work, since its performance is similar to that of methods that use solar irradiance as input, with *c* values higher than 0.90.

Other methods, such as Camargo and Hargreaves-Samani, had less accuracy, especially during periods of high evapotranspiration, which coincide with the dry season. Methods with lower accuracy in periods of high evapotranspiration may lead to meaningful errors in irrigation management. Since crop evapotranspiration is calculated as a function of ETo, it is worthwhile to use methods that do not display this behavior or at least methods that yield good results after calibration.

In addition to its low r^2 (Figures 2D e 3D), the method of Hargreaves-Samani also had “very poor” and “tolerable” performance for the studied periods in the rainy and dry season, respectively, and for all the cities (Table 2); therefore, this method is not recommended for the region. Sanches et al. (2015) found a “very poor” performance for this model in the North Region of Brazil, and the model’s performance was “tolerable” after calibration.

Chagas et al. (2013) also observed a ‘tolerable’ performance for this method during the dry season, when the method overestimated ETo by 20.55% in Rio Real, Bahia State. Despite its improvement from the rainy to dry seasons, this method presented errors of 1.14 mm day^{-1} during the wet period and 0.58 mm day^{-1} during the dry season (Table 2).

The method of Camargo had very poor performance, in addition to high NRMSEs for all the cities and periods, with errors exceeding 1 mm day^{-1} regardless of the time of year (Table 2). According to Cunha et al. (2013), the method of Camargo is derived from the method of Thornthwaite and is appropriate for tropical and equatorial climates; regardless, this method had very poor performance in the studied region and therefore is not recommended.

The very poor performance of the method of Camargo found for all comparison criteria confirm the results of Borges Júnior et al. (2012) for the microregion of Garanhuns, Pernambuco State, in which correlation coefficients equal to 0.24 and 0.54 were indicated during spring-summer and fall-winter, respectively.

The FAO 24 Radiation method had excellent performance during the rainy season, with an SEE of only 0.5 mm day^{-1}, and good performance and good precision during the dry season for all the cities, despite producing the largest SEE during this season (Table 2). The use of calibration coefficients is recommended to improve the performance of this method. The FAO 24 Radiation method, which is an adaptation of the method of Makkink, had good performance in the studied region, as well as in other regions of Brazil (Cavalcante Jr. et al., 2011; Cunha et al., 2013; Lacerda & Turco, 2015).

The method of Priestley-Taylor showed better r^2 values during the rainy season, for all the studied cities; however, the method showed only good performance (Table 2) for all the studied periods. According to Cavalcante Jr. et al. (2011), this method produces bad performance during the dry season. On the other hand, according to the same authors, the method shows a meaningful improvement in performance during the rainy season; this conclusion is similar to that of Caporusso and Rolim (2015), who observed that the method is more accurate in the summer and underestimates results during winter. Sanches et al. (2015) also classified the method as good before calibration and excellent after calibration in the North Region of Brazil.

The Makkink method showed excellent performance during the dry season for all the cities; however, this method had good performance and RMSEs ranging from good (14.22%) to acceptable (22.13%) during the dry season. This method may have better robustness in the estimation of ETo because it uses both solar irradiance and psychrometric parameters.

The methods of Makkink, Priestley-Taylor and FAO 24 Radiation were calibrated by linear regression since they showed better performances (Table 3). The ETo values calculated by the calibrated models were compared to the ETo calculated by the standard method by using linear regression. The calibrated equations had good accuracy, in other words, intercept and slope values of approximately 0 and 1, respectively. The Pearson correlation coefficient, as expected, remained the same. For this reason, only the equations with high r and r^2 values were calibrated.

The statistical parameters d, c, NRMSE, and SEE were highly improved in the calibrated methods. It is worthwhile to highlight that calibrations were performed with the purpose of correcting the trend of data in relation to the FAO 56 Penman-Monteith results and did not change the dispersion of data. The performance of the Priestley-Taylor method ranged from good to excellent during the rainy season and from good to very good during the dry season, reducing its error from 0.86 to 0.19 and from 0.68 to 0.35 mm day^{-1}, respectively.

Table 3. Performance classification of different methods with correction factors for the estimation of ETo compared to the value obtained by the FAO 56 Penman-Monteith method, for municipalities in the northeast of Pará, during both the rainy season and dry season.

Method	*d*	*r*	*c*	NRMSE (%)	SEE (mm day^{-1})	Classification	Equation with correction factor
Rainy season							
Priestley-Taylor	0.98	0.98	0.97	4.49	0.19	Excellent	$ETo = \left[\frac{1.26\ \frac{\Delta}{(\Delta+\gamma)}.(Rn-G)}{1.11}\right] - 0.41$
Dry season							
Makkink	0.95	0.91	0.86	6.42	0.33	Very good	$ETo = \left[\frac{0.61 \times \frac{\Delta}{(\Delta+\gamma)} \times Rg - 0.12}{0.78}\right] - 0.40$
Priestley-Taylor	0.94	0.89	0.83	6.86	0.35	Very good	$ETo = \left[\frac{1{,}26.\frac{\Delta}{(\Delta+\gamma)}.(Rn-G)}{0.88}\right] - 1.23$
FAO 24 Radiation	0.98	0.97	0.95	4.65	0.24	Very good	$ETo = \left[\frac{(a+b).\frac{\Delta}{(\Delta+\gamma)}.Rg}{1.30}\right] - 0.72$

d – Willmott index, r – Pearson correlation coefficient, c – performance index, NRMSE - normalized root mean square error, SEE - standard error of estimate.

The performance of the FAO 24 Radiation method also increased from good to very good during the dry season. The Makkink method was calibrated only for the dry season, and its performance increased from good to very good.

The Blaney-Criddle FAO 24, Turc and Regression methods had the best performance in comparison to the Penman-Monteith FAO 56 method, according to all the statistical criteria; therefore, such methods are reliable and recommended in the region. Both the Camargo and Hargreaves-Samani methods had worse performance for all the compared criteria in relation to those of other methods.

Other methods, even the ones that were better than Camargo and Hargreaves-Samani, may be considered less reliable than the best methods (Blaney-Criddle FAO 24, Turc and Regression); however, after calibration, these other methods showed meaningful improvements, and therefore, their use is recommended.

Among the methods that presented the best performance in the estimation of ETo for both periods of the year, only one of them is temperature-based (Blaney-Criddle), one is radiation-based (Turc) and the third, which was developed through linear regression (regression), considers both solar energy and the evaporating power of the air. All of these methods yield errors smaller than 0.33 mm day^{-1}, which is a very important detail for those producers who seek a better estimation of ETo and consequently ETc for irrigation purposes in the region.

The other methods recommended after calibration (Makkink, FAO Radiation, and Priestley-Taylor) also depend on solar radiation, but their estimates produced less than 0.35 mm of error on a daily basis, especially in the less rainy season, which guarantees similar precision in the estimation of ETo and ETc.

However, it is important to note that the meteorological observation network in the North Region of Brazil is much more limited than that in the rest of the country in relation to the number of stations (Souza et al., 2007), making access to reliable data a problem for the great majority of the region's producers. Methods that depend on fewer meteorological variables are highly beneficial to producers who plan to adopt irrigation management in the region, especially during the dry season, since they will only need a few sensors in their areas for ETo estimation.

For example, although the Blaney-Criddle method is considered temperature-based (Kashyap & Panda, 2001), the method requires data on the relative air humidity, wind speed and insolation in addition to air temperature, which makes it a laborious method. On the other hand, the Makkink method uses solar radiation data, and the Turc method uses temperature and solar radiation data.

In any case, all the methods proposed and recommended for the region are more practical than the FAO standard method because they require a smaller number of variables, allowing the producer or researcher to choose which method to use depending on the availability of meteorological data in the region.

Conclusion

The Turc, Blaney-Criddle FAO 24, and Regression methods, which did not need any calibration, yielded the best classification based on all statistical criteria, with errors less than 0.38 mm day^{-1}, especially during the dry season, when accurate estimates are necessary for irrigation strategies. The Priestley-Taylor, Makkink and FAO 24 Radiation methods were significantly improved through calibration, which reduced their errors to less than 0.5 mm day^{-1}; therefore, these methods may be used in the northeast region of Pará. The Camargo and Hargreaves-Samani methods yielded the worst classification for all the cities and comparison criteria in relation to the other methods, with errors that exceeded 1 mm day^{-1}; therefore, they are not recommended in the studied regions.

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