

Original Research Article

Comparison of Reference Evapotranspiration Estimates obtained by Different Methods

in relation to the Penman-Monteith Method in Cerrado Environment, Brazil

ABSTRACT

Water is the most limiting resource for crop production, however, erroneous estimates of the amount needed to be applied can increase production costs, influence plant nutrition and contaminate the ecosystem. Thus, the objective of this work was to compare the values of E_t_0 obtained by the methods of Blaney-Criddle, solar radiation and Ivanov with the values resulting from the use of Penman-Monteith method in cerrado environment, Brazil. To estimate evapotranspiration values were used the daily data of the maximum and minimum temperatures, wind speed, amount of daylight hours and relative humidity of the years of 2010 and 2011. To compare the estimated values, the parameters of the regression equation a and b, coefficient of determination (r^2), correlation coefficients (r), agreement (d) and confidence (c) were considered. Based on the Penman-Monteith method, it was verified that all the other methods evaluated overestimate the values of E_t_0 during the whole evaluated period. Despite this, it was founded a good correlation between the Blaney-Criddle method and the Penman-Monteith method. The solar radiation and Ivanov methods presented low coefficient of determination when compared to the PNM method. It was concluded that the reference evapotranspiration, on a daily scale, can be quantified using the Blaney-Criddle method instead of the Penman-Monteith method. Furthermore, the solar radiation and Ivanov methods, despite the good agreement and performance indexes, present the greatest distortions during the year.

Key words: Agricultural meteorology; Blaney-criddle; Ivanov; Penman-Monteith; solar radiation.

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29 1. INTRODUCTION

30 Water is the most limiting resource for crop production [19] and projections by the
31 Organisation for Economic Co-operation and Development [21] indicate that water scarcity
32 will affect 2/3 of the world's population by 2050. Furthermore, the world population is
33 expected to increase to 9.1 billion people by 2050 [30]. This scenario suggests that water use
34 should be increasingly optimized.

35 Of the 200 million tons of grain produced in the country in 2015/2016, about 24%
36 originates in the state of Mato Grosso (MT) [5]. In relation to the irrigated area, the state has
37 approximately 178 thousand ha irrigated (3.1% of the total of the country) [1]. The cerrado of
38 the Mato Grosso state, Brazil, is recognized as one of the regions with the largest irrigated
39 area in Brazil, entering the area of occurrence of the Brazilian Tropical Rainforest, suggesting
40 the occurrence of quite distinct environmental scenarios, especially regarding climatic
41 variables [28]. However, despite the importance of cerrado in national agricultural
42 production, few studies allow efficient quantification of reference evapotranspiration for the
43 regional edaphoclimatic cerrado conditions.

44 Evapotranspiration is defined as being the phenomenon that occurs from the
45 combination of two processes: i) evaporation, in which the passage of water from the liquid
46 to the gaseous state occurs, after the water vapor absorbs the energy of the medium called
47 latent heat of evaporation and, ii) transpiration, which is the evaporation of water used in the
48 various metabolic processes of plants [24].

49 The reference evapotranspiration (E_t0) is related to the effect of the atmospheric
50 demand on the water requirements of the plants, being estimated from the elements of the

climate [24]. Therefore an accurate determination of E_{t0} is of fundamental importance for good irrigation management.

In this context, there are several methods to calculate the E_{t0} , the main one being the method proposed by Penman-Monteith, which is considered by many, the standard method to be used anywhere without calibration [22, 31]. However, this method requires a high number of climatic variables and this has made it unfeasible in many cerrado regions. Contrary to this, several publications point to other methods, which have a lower requirement and complexity, which could be used (depending on the edaphoclimatic conditions of the region) in some Brazilian regions, such as the Blaney-Criddle, Radiation Solar and Ivanov equations [27, 29]. Some of these methods are based on a single climatic variable such as solar radiation [4, 16] or temperature [12].

In this sense, the evaluation and comparison of different methods of estimating evapotranspiration in the state of Mato Grosso could contribute to reduce water consumption, optimize irrigation systems and increase the efficiency of water use, resulting in environmental and economic benefits for irrigated agriculture [9].

. Thus, the objective of this work was to compare the values of E_{t0} obtained by the methods of Blaney-Criddle, solar radiation and Ivanov with the values resulting from the use of Penman-Monteith method in cerrado environment, Brazil.

2. MATERIAL AND METHODS

We used daily data of mean air temperature ($^{\circ}\text{C}$), maximum ($^{\circ}\text{C}$), minimum ($^{\circ}\text{C}$), relative humidity (%), wind speed (m s^{-1}) and total sunshine for the years 2010 and 2011 obtained from the climatological station code OMM 83363, located in the municipality of Santo Antônio do Leverger, MT, Brazil ($15^{\circ} 49' \text{S}$ and $55^{\circ} 25' \text{W}$ with 790 m altitude).

75 It should be emphasized that, despite the data series being only two years, the
 76 unavailability of information for studies of this nature has caused several researches to be
 77 developed with even smaller series [7].

78 The insolation was measured using the heliograph. Estimates of reference
 79 evapotranspiration (Et_0) were obtained by the Penman-Monteith methods parameterized by
 80 Allen *et al.* [3] for the 24 hours' time interval (Eq. 1), Blaney-Criddle [4], modified by
 81 Doorenbos and Pruitt [11] (Eq. 2), Solar Radiation (Eq. 3) and Ivanov [14] (Eq. 4).

$$Et_0 = \frac{0,408\Delta(R_n - G) + \frac{900\gamma u_2(e_s - e_a)}{(T+273)}}{\Delta + \gamma(1 + 0,34u_2)} \quad \text{Eq. (1)}$$

82 where Et_0 is the estimated reference evapotranspiration (mm day^{-1}), R_n is the surface
 83 radiation balance ($\text{MJ m}^{-2}\text{day}^{-1}$), G is the sensible heat flux in the soil ($\text{MJ m}^{-2}\text{day}^{-1}$), T is the
 84 air temperature ($^{\circ}\text{C}$), u_2 is the wind velocity at 2 m height m s^{-1} , e_s is the saturation pressure
 85 of water vapor (kPa), e_a is the partial water vapor pressure (kPa), Δ is the slope of the water
 86 vapor saturation pressure curve ($\text{kPa } ^{\circ}\text{C}^{-1}$); and γ is the psychrometric constant ($\text{kPa } ^{\circ}\text{C}^{-1}$).

$$Et_0 = a + b p (0,46 T + 8,13) \quad \text{Eq. (2)}$$

87 Where a e b are the coefficients of the linear equation, p is the daily percentage of the annual
 88 average of hours of solar brightness; and T is the average temperature in $^{\circ}\text{C}$.

$$Et_0 = c * W * R_s \quad \text{Eq. (3)}$$

89 where c is the adjustment factor that varies as a function of the average relative humidity of
 90 the air and the average speed of the wind to 2 meters of height [10], W is the factor, which
 91 includes the effects of temperature and altitude on the relationship between soil surface
 92 radiation and reference evapotranspiration [11] and R_s is the average solar radiation
 93 expressed in equivalent evaporation (mm day^{-1}).

$$Et_0 = 0,006(25 + T)^2 \left(1 - \frac{U_R}{100}\right) \quad \text{Eq. (4)}$$

94 where Et_0 is the Reference evapotranspiration by Ivanov (mm day^{-1}), T is the average air
95 temperature ($^{\circ}\text{C}$), and U_R is the relative humidity (%).

96 The radiation balance (R_n) was calculated according to the proposal of Allen *et al.* [3],
97 being described as the difference between short-wave radiation and long-wave radiation,
98 from the estimation of solar radiation by the Angstrom equation, adopting coefficients a and
99 b of 0.25 and 0.50, respectively, and one Albedo of 0.23. The standardized equations for the
100 calculation of all the parameters of Eq. 1 are presented in Doorenbos and Pruitt [11].

101 Regression analysis was performed between the values estimated by the different
102 methods, considering the linear model. The analysis of the results was done according to the
103 agreement index (d) (Eq. 5), according to Willmott [32, 33] and Camargo and Sentelhas [6]
104 methodologies, confidence or performance (c) (Eq. 6) [2], in addition to the correlation
105 coefficients (r) and determination (r^2).

$$d = 1 - \left[\frac{\sum_{i=1}^N (P_i - O_i)^2}{\sum_{i=1}^N (|P_i - O| + |O_i - O|)^2} \right] \quad \text{Eq. (5)}$$

106 where P_i is the predicted or estimated by the methods of Blaney-Criddle, Solar Radiation and
107 Ivanov, O_i is the value of Et_0 observed by the Penman-Monteith equation (mm day^{-1}), and O
108 is the mean of the observed values.

$$c = r \cdot d \quad \text{Eq. (6)}$$

109 where c is the confidence index " c ", and d is the Willmott's concordance index [33].

110 The table 1 presents the criteria used to interpret the performance of the estimation
111 methods of Et_0 by the indices " c " and " r ", respectively.

112

113 **Table 1. Criteria for interpretation of the performance of the methods of estimation of**
 114 **E_{t0} by the index "c" and correlation values "r" proposed by Camargo and**
 115 **Sentelhas [6].**

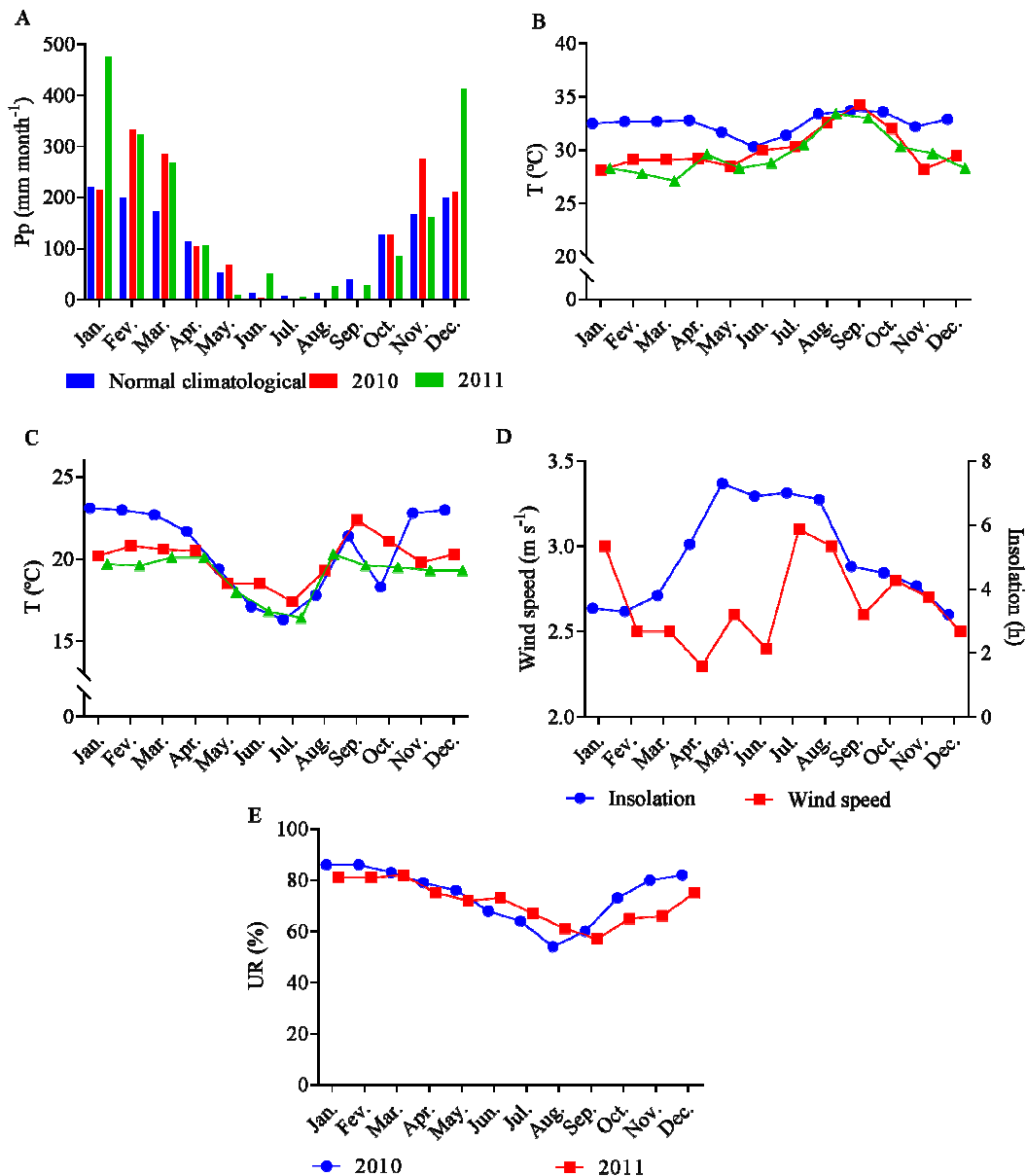
Value of "c"	Performance
> 0,85	Great
0,76 a 0,85	Very good
0,66 a 0,75	Good
0,61 a 0,65	Median
0,51 a 0,60	Affordable
0,41 a 0,50	Bad
- 0,40	Terrible
Value of "r"	Precision
0,9-1,0	Almost perfect
0,7-0,9	Very high
0,5-0,7	High
0,3-0,5	Moderate
0,1-0,3	Low

116 Source: Camargo and Sentelhas [6].

117

118 **3. RESULTS AND DISCUSSION**

119 The Fig 1 shows the average monthly variations of the climatic elements required to
 120 calculate the reference evapotranspiration, which were obtained at the meteorological station
 121 of the Federal Institute of Mato Grosso, municipality of Santo Antônio do Leverger, MT,
 122 located in the southeast of the state of Mato Grosso, Brazil, in the period of 2010 and 2011.



123
 124 **Fig 1. Precipitation values (A), maximum temperature (B), minimum temperature (C),**
 125 **wind speed and solar insolation (D) and relative humidity (E) from the main**

climatological station of São Vicente da Serra, in Years of 2010 and 2011, as well as the normal climatological in terms of rainfall (1961-1991).

The precipitation during the period of the experiment, in general, had a behavior close to that of the climatological normal, with the rainy season comprising the months of **October to April** and the dry season the months of **May to September**. The intensity of the precipitation in the period of the experiment exceeded the climatological normal in the months of **January, February, March, November and December**, highlighting the month of **January** of 2011 in which the total precipitation corresponded to more than twice the rain expected for the normal climatic conditions (Fig 1A).

For the whole period of the experiment, the maximum temperatures were below the climatological normal, except in the period from **June to September**. The behavior of the minimum temperatures for the period of the experiment was close to that of the climatological normal, except in the months of January, February and March with values below the normal climatological. Among the months, the highest and lowest temperatures were observed between September and April, corresponding to the rainy season, and milder temperatures in the months of May to August (Fig 1A).

The behavior of the sunshine indicated that the smallest number of hours of sunshine occurred in the period from October to April, due to increased cloudiness in the rainy season of the region that is characterized by the presence of intense convective activity in the months of higher radiative heating (Fig 1B). The wind speed over the months studied varied around 2.7 m s^{-1} (Fig 1B).

The behavior of medium air (Fig 1C), precipitation and maximum and minimum temperatures characterize the rainy summer with high temperatures and a dry winter with milder temperatures in the studied region. Similar results were found by Souza *et al.* [25]

151 when, studying the 13 climatological stations of the state of Mato Grosso, proposed the
152 climatic water balance and the climatic classification of the state.

153 The Fig 2 shows the daily values of reference evapotranspiration (E_t) calculated by the
154 PNM, IV, RS and BC methods for the years 2010 and 2011, in four seasons of the year, being
155 chosen according to their importance in defining The seasons by the solstices (winter/June
156 and summer/December and equinoxes (autumn/March and spring/September).

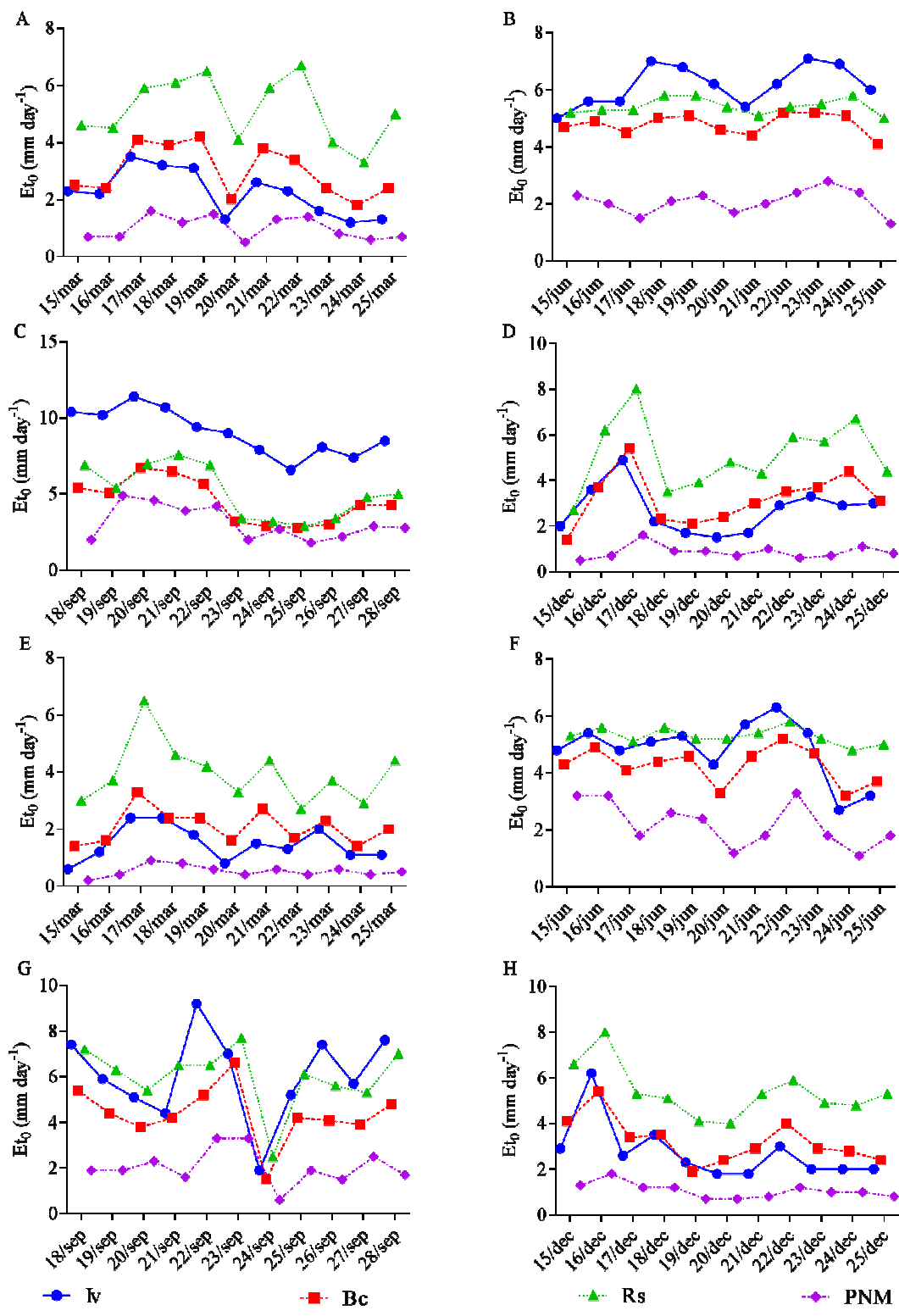


Fig 2. Daily behavior of reference evapotranspiration (E_t) by Penman-Monteith (PNM) (PMN), Blaney-Criddle (BC), Solar Radiation (RS) and Ivanov (IV) for 2010 (A, B, C and D) and 2011 years (E, F, G and H).

Based on the PNM method, it was verified that all the other methods evaluated overestimate the values of E_t during the whole evaluated period. The method IV overestimated mainly in June (winter solstice) and September (spring equinox), suggesting that the method, based on the use of only the temperature and relative humidity of the air, does not allow adequate inferences in the months that comprise the dry season of the region. These results were also observed by Alencar *et al.* [2] evaluating the IV method in Uberaba, MG, which observed an overestimation of E_t in the period of lower relative humidity. The BC method was the one that had the least variable behavior throughout the year, but presented an overestimate behavior throughout the year. Similar behavior was observed by Alencar *et al.* [2].

In fact, the Penman-Monteith method was an improvement on Penman's original method, and several studies in Brazil and in the world have proven that the Penman-Monteith method is quite accurate [13, 15, 34, 35), being, for this reason, widely used as a standard of comparison with the other methods.

Despite the overestimation of evapotranspiration (mm day^{-1}) obtained by the Blaney-Criddle, solar radiation and Ivanov methods, these methods were found to present, if necessary, a potential for use in a closed environment. That is, the calibration should be carried out for the local conditions in order to improve them to the point where they can be used even in substitution for the Penman-Monteith method. In this sense, in a study by Sentelhas *et al.* [24] for 12 locations in southern Ontario, Canada, studying methods that use only temperature data and the Penman-Monteith method, which uses only maximum and

183 minimum temperatures [3], observed that the Hargreaves method, after some adjustments,
184 was the best option to estimate E_{t0} .

185 The values for the parameters of the regression equation (a and b) were significant
186 ($P<0.05$) in all cases. It is also observed that the Blaney-Criddle method presented the best
187 performance compared to other methods, with linear coefficients (b) with values close to 1
188 (Figs 3A and 3E).

189 The determination coefficients obtained between the reference evapotranspiration
190 estimated on a daily scale by the PNM method and by the BC, RS and IV methods for the
191 years 2010 and 2011 (Fig 3) were 0.80, 0.78 (Fig 3A, 3E), 0.69, 0.78 (Fig 3B, 3F) and 0.59,
192 0.55 (Fig 3C, 3G), for the BC, RS and IV methods, respectively.

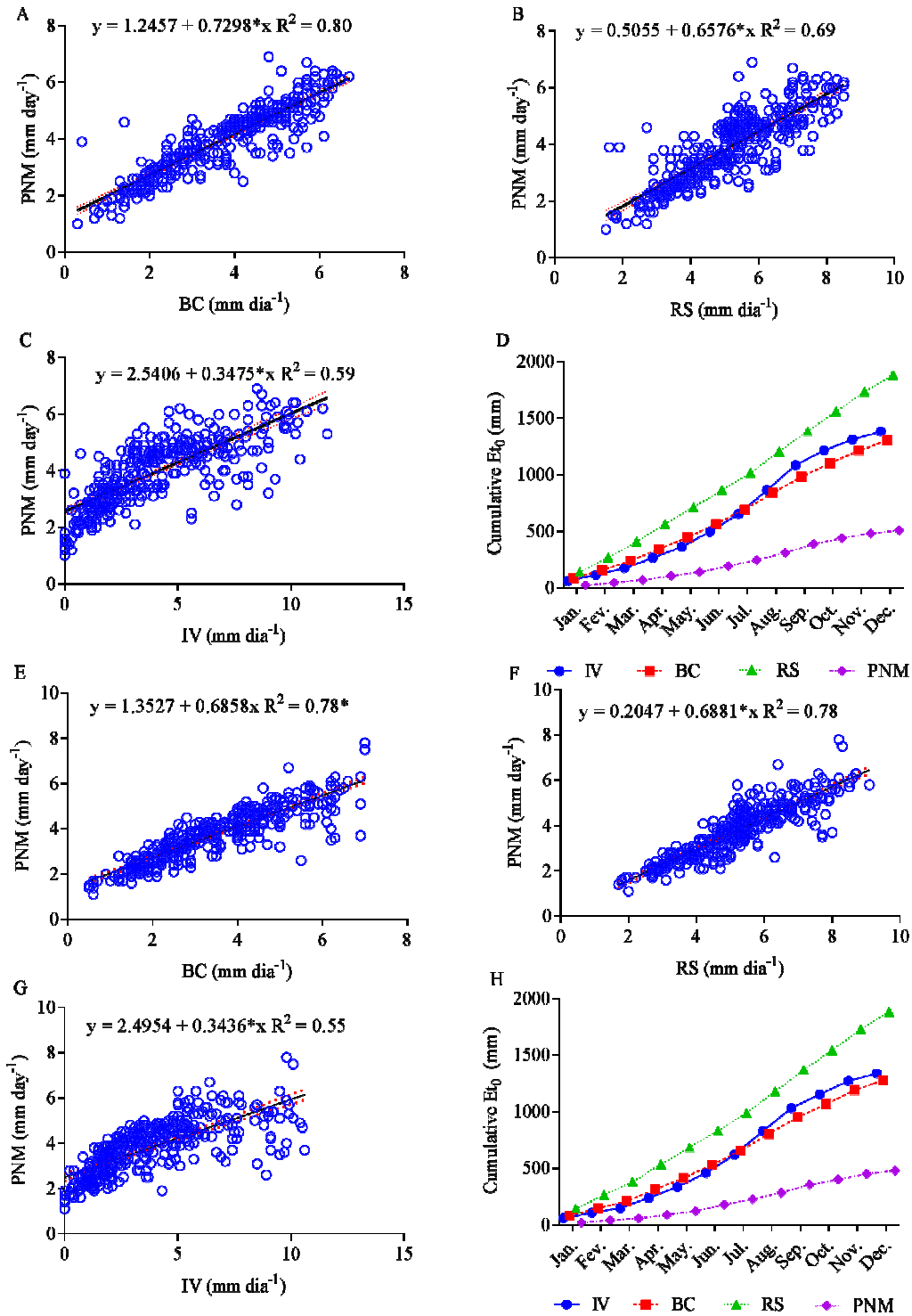


Fig 3. Coefficient of determination (r^2) between the reference evapotranspiration values obtained by the Penman-Monteith method (PNM) and the reference evapotranspiration

obtained by the Blaney-Criddle (BC) method (A); Penman-Monteith method (PNM) (mm day⁻¹) and the reference evapotranspiration obtained by the Solar Radiation (RS) method (mm day⁻¹) (B); Penman-Monteith method (PNM) (mm day⁻¹) and the reference evapotranspiration obtained by the Ivanov (IV) method (mm day⁻¹) (C); and the cumulative average evapotranspiration by the different methods in 2010 (D) and 2011 (E, F, G and H). **(P<.05).*

According to Fig 3A and 3E, a good correlation was found between the BC method and the Penman-Montheith method; on the other hand, the RS and IV methods presented low coefficient of determination when plotted using the PNM method.

Although the RS and IV methods showed the lowest correlation indices with the standard Penman-Montheith method, they were classified as "very good" by the classification of index c and as "very high" in the index R of Camargo and Sentelhas [6]. Furthermore, the RS and IV methods showed concordance indices, according to Willmott [33], of 0.97 and 0.97, respectively (Table 2).

These results indicate that the method that suggests the equally relevant potential to estimate the reference evapotranspiration among the methods studied, when compared to the FAO standard of Penman-Montheith, is the Blaney-Criddle method (Figs 3A and 3E). This is justified by the fact that the Blaney-Criddle method obtained higher coefficient of determination in both years (2010 and 2011). In addition, the lowest coefficient of determination, in the estimates for the year 2010 and for 2011, was obtained by the Ivanov method (Figs 3C and 3G). The solar radiation method, in turn, despite having a coefficient of determination identical to that of Blaney-Criddle in 2011, presented a low value for the year 2010 ($r^2 = 0.69$) (Figs 3B and 3F).

These results agree with those obtained by Reis et al. [23], which, in a comparative study of empirical methods, for estimating E_{t0} , compared to the standard Penman-Monteith universal method, for the climatic conditions of the municipalities of Sooretama, Cachoeira do Itapemirim and Venda Nova do Imigrante, respectively, in the northern, southern and mountainous regions of the State of Espírito Santo, Brazil. For the climatic conditions of the localities where the work was performed, for the dry period, the methods that presented the best estimates followed the following decreasing order: Blaney-Criddle and solar radiation.

The BC method presented the best performance among the methods in that it presented coefficient of determination (r^2) of 0.80 (Fig 3A, 3E) and agreement index of 0.99 (Table 2), confirming good agreement with the standard method (Table 1), according to the interpretation of Camargo and Sentelhas [6].

Comparing PNM with RS, it was obtained the value of 0.97 for the concordance index (d), indicating a good agreement between the methods. For the confidence index (c) and correlation coefficient (r), it was obtained values of 0.83 and 0.85, respectively; therefore, the confidence and high accuracy were lower than the BC method. Although the RS method has performed well, it is a method that requires more meteorological data, which are often not available in the region, making it difficult to use. Tanaka et al. [27] verified an overestimation of E_{t0} with the use of the RS method in evaluations in the state of Mato Grosso, indicating that this method requires local calibrations for reliable estimation of E_{t0} .

Table 2. Results of the concordance (d), correlation (r) and confidence (c) tests for the different methods in relation to Penman-Monteith for São Vicente da Serra, MT, in the period of 2010 and 2011.

Methods	d	r	c
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PNM x BC	0,99	0,92	0,92
PNM x RS	0,97	0,85	0,83
PNM x IV	0,97	0,81	0,81

For PNM x IV, the value for agreement (d) observed was 0.97, indicating a near perfect agreement between the methods (Table 2), but, it was noted a lower result for the confidence index (c) and correlation coefficient (R), which were 0.81 and 0.81, respectively, which interpreted, represented high agreement with the Penman-Monteith method, however, when compared to the results in terms of the confidence and precision indices, it was lower than other methods.

Mendonça *et al.* [18], comparing different methods of estimation of reference evapotranspiration and comparing them with the estimation of the class A tank, for the northern region of Rio de Janeiro, Brazil, observed that the solar radiation method tended to overestimate E_{t0} by 25.7 %. In turn, Tagliaferre *et al.* [26] with the same objective, verified that the BC and RS method presented better performances for the estimates of E_{t0} in all the periods studied for the region of Eunápolis, Bahia, differing therefore from the results found in this work.

Alencar *et al.* [2] observed that the BC method presented the best results for the period of high demand, represented by high precision indexes and small associated errors for the region of Uberaba, Minas Gerais. Chauhan and Shrivastava [8] also compared the Blaney-Criddle and solar radiation methods with the standard Penman-Montheith method and the results led to the conclusion that the BC method presented the best performance, followed RS, with efficiencies of 83% and 53.8%, respectively.

The researches with estimates of the E_{t0} translate variation in the behavior of the models in the different Brazilian regions, as reported by Alencar *et al.* [2] beyond Melo and

Fernandes [17]. Thus, the selection of the method to be employed depends on locally verified factors such as climatic conditions, availability of meteorological data, complexity of the method, grouping of the data considered and costs. Therefore, models that do not perform satisfactorily for proper estimates in a region should be evaluated and, if necessary, calibrated for local or regional climatic conditions.

Finally, due to the results presented in this work, with the unavailability of input data for the Penman-Montheith method, it is justified to use alternative methods such as Blaney-Criddle. However, in order to adapt them to the specific condition of the cerrado of the state of Mato Grosso, Brazil, the Blaney-Criddle, Solar Radiation and Ivanov method need to go through adjustments (calibrations), evidencing, therefore, that for the adoption of a method, one should focus on the climatic conditions and/or similarities in which it was developed.

4. CONCLUSIONS

The Blaney-Criddle reference evapotranspiration method was the method that presented the best estimates when compared to the Penman-Montheith standard for the cerrado environment, Brazil, however, it emphasizes the need for method calibration to local conditions. That is, the Blaney-Criddle reference evapotranspiration method can, after undergoing calibration, effectively replace the Penman-Montheith method under Brazilian cerrado conditions.

Solar radiation and Ivanov, although relatively simple methods are not recommended for the cerrado region of Mato Grosso state, Brazil.

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