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Evapotranspiration of sorghum from the energy balance by METRIC and STSEB

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ABSTRACT: The estimate of the actual surface evapotranspiration (ET) contributes to quantifying the water needs of crops. An alternative to the use of lysimeter for an accurate estimation of water needs, which has proved to be of great value in recent years, is the use of remote sensing combined with models based on surface energy balance. There is wide variety of models that can be classified into two types: one-source models, such as the Mapping EvapoTranspiration at high Resolution with Internalized Calibration (METRIC) algorithm, or two-source models, such as the Simplified Two-Source Energy Balance (STSEB). The objective of this study was to analyze how METRIC and STSEB can be used to estimate ET, in comparison with the lysimeter data, for the different stages of development of the sorghum crop in Apodi, RN, Brazil. The accuracy of both models in the daily ET estimation for the semi-arid conditions of the experiment, with RMSE values of 0.8 and of 0.7 mm d^{-1} through METRIC and STSEB, respectively, is considered acceptable for irrigation management purposes. The errors obtained with METRIC at an instantaneous scale were 60, 50, 130 and 5 W m^{-2} for Rn, LE, H and G, respectively, on the other hand, using STSEB these errors were of 40, 70, 120 and 21 W m^{-2} for Rn, LE, H and G, respectively. The METRIC and STSEB models are very similar when it comes to providing information on water needs of the sorghum.

Key words: *Sorghum bicolor*, irrigation management, remote sensing, irrigation

Evapotranspiração do sorgo a partir do balanço de energia por METRIC e STSEB

RESUMO: A estimativa da evapotranspiração real da superfície (ET) contribui para quantificar as necessidades hídricas dos cultivos. Uma alternativa ao uso do lisímetro para uma estimativa precisa das necessidades hídricas, e que provou ser de grande valor nos últimos anos, é o uso do sensoriamento remoto combinado com modelos baseados no balanço de energia na superfície. Existe uma grande variedade de modelos que podem ser classificados em dois tipos: modelos de uma fonte, como o algoritmo Mapping EvapoTranspiration at high Resolution with Internalized Calibration (METRIC), ou de duas fontes, como o Simplified Two-Source Energy Balance (STSEB). O objetivo deste estudo foi analisar como METRIC e STSEB podem ser usados para estimar a ET, em comparação com os dados do lisímetro, para as diferentes fases de desenvolvimento da cultura do sorgo em Apodi, RN. O grau de precisão de ambos modelos, na estimativa de ET diária, para as condições semiáridas do experimento, com valores de RMSE de 0,8 e de 0,7 mm d^{-1} através dos modelos METRIC e STSEB, respectivamente, considera-se aceitável para fins de manejo de irrigação. A escala instantânea dos erros obtidos com METRIC foram de 60, 50, 130 e 5 W m^{-2} para Rn, LE, H e G, respectivamente. Por outro lado, usando STSEB estes erros foram de 40, 70, 120 e 21 W m^{-2} para Rn, LE, H e G respectivamente. Os modelos METRIC e STSEB são muito semelhantes quando se trata de fornecer informações sobre as necessidades hídricas do sorgo.

Palavras-chave: *Sorghum bicolor*, manejo de irrigação, sensoriamento remoto, irrigação

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Introduction

Currently, there has been an increasing number of irrigated areas in Northeastern Brazil, a region characterized by problems caused by water scarcity. In this regard, it is evident that most of these areas require adequate irrigation management, which can be accomplished by estimating the water needs of crops in the different stages of their phenological cycle. An accurate estimation of actual evapotranspiration (ET) makes it possible to replace a quantity of water closer to the actual needs, hence being a key indicative in irrigation management, and can be determined using remote sensing techniques and from models based on the surface energy balance.

Energy balance models can be classified into two types: one-source models (Oliveira et al., 2014; Paço et al., 2014; González-Piqueras et al., 2015; Madugundu et al., 2017) or two-source models (Sánchez et al., 2011; González-Dugo et al., 2012; Sánchez et al., 2014). These models are based on the surface energy balance through the determination of the latent heat flux (LE), estimating net radiation (Rn), sensible heat flux (H) and soil heat flux (G) (González-Piqueras et al., 2015).

The Mapping EvapoTranspiration at high Resolution with Internalized Calibration (METRIC), a one-source model, estimates the energy balance fluxes without differentiating between vegetation cover and soil, which allows calibrating the model and dimensioning the flux values of the entire image from two pixels that define extreme conditions of ET, bare soil with values close to zero and a reference crop (Allen et al., 2007). The Simplified Two-Source Energy Balance (STSEB) model is a two-source model, considered of solid physical basis as it requires precise input data from both ground agrometeorological stations and remote platforms (under atmospheric corrections in the visible and near-infrared range and also of emissivity in thermal infrared).

In this context, this study aimed to evaluate the METRIC and STSEB models, comparing the data measured in the field of the sorghum crop, as well as to monitor the water needs of this crop during its growth cycle.

Material and Methods

The study area (Figure 1) is located in Apodi, RN, Brazil, with the following coordinates: 5° 37' 38" S, 37° 49' 55" W, 150 m of altitude. According to Köppen's climatic classification, the climate is BSh (very hot and semiarid), with average annual rainfall of 893 mm $year^{-1}$ and average annual temperature of 27.1 °C, according to the Instituto Nacional de Meteorologia (Ramos et al., 2009).

The studied plot of sorghum had an extension of 3.6 ha, with the variety Ponta Negra. The spacing was 0.10 m between plants and 0.75 m between rows. The crop was irrigated by sprinklers, with a flow rate of 1.8 m^3 h^{-1}, according to the specifications. The study period included two experiments from April 4, 2012 (Julian day, JD 95) to July 24, 2012 (JD 206) and from October 12, 2012 (JD 286) to January 12, 2013 (JD 12).

In order to measure the four components of the surface energy balance, a 4-component CNR4 net radiometer (Kipp & Zonen BV., Delft, The Netherlands) was installed in the area to

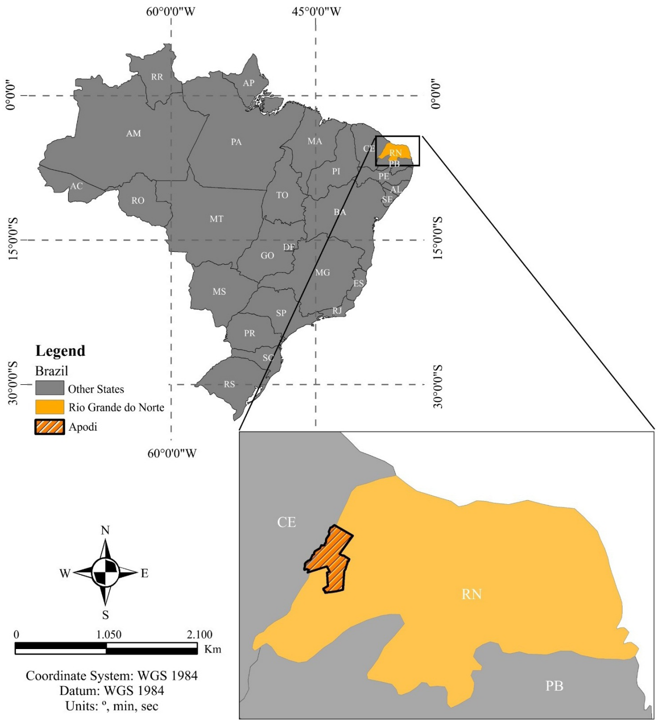


Figure 1. Location of the municipality of Apodi, RN, Brazil

measure Rn (W m^{-2}) above the vegetation cover. G values were measured at two positions, through two soil heat flux sensors, model HFP01 (Hukseflux Thermal Sensors BV., Delft, The Netherlands), buried at 0.02 m from the surface, one placed exactly under the vegetation cover, and the other in the space between rows. For the measurement of latent heat flux (LE), two lysimeters with 2.7 m^2 area and 1 m depth were installed. Sensible heat flux (H) was obtained, in this case, from the remainder of the energy balance equation (H = Rn - G - LE). All sensors were connected to a CR3000 datalogger (Campbell Scientific, Inc., Logan, Utah, USA). ETo (reference evapotranspiration) values were estimated using meteorological data from an INMET station located within the farm, very close to the study area.

This study used five images of Landsat 7-ETM+ covering the different stages of sorghum development. The dates of the images for the first experiment were: May 12 (Julian Days - JD 133), May 28 (JD 149) and June 13 (JD 165) of 2012. For the second experiment, the dates were: November 20 (JD 325) and December 22 (JD 357) of 2012.

The theoretical basis of the METRIC method was described by Allen et al. (2007) and the simplified two-source method by Sánchez et al. (2011). Both models determine the LE, directly related to evapotranspiration (ET), as a remainder of the energy balance equation (Eq. 1):

$$LE = Rn - G - H \quad (1)$$

where:

LE - Latent heat flux, W m^{-2};
Rn - net radiation, W m^{-2};
G - soil heat flux, W m^{-2}; and,
H - sensible heat flux, W m^{-2}.

The METRIC model uses the following equation (Eq. 2) to determine net radiation (Rn) in each pixel:

$$Rn = (1-\alpha)R_g - R_{atm} - R_{surf} - (1-\varepsilon_0)R_{atm} \quad (2)$$

where:

Rn - Net raduation, W m^{-2};
α - albedo, dimensionless;
R_g - incident shortwave radiation, W m^{-2};
R_{atm} - incident longwave radiation, W m^{-2};
R_{surf} - upward longwave radiation, W m^{-2}; and,
ε_0 - surface emissivity.

The incident longwave radiation (R_g) was calculated according to the ASCE-EWRI model described by Allen et al. (2007), from the hour, Julian day, location, and terrain slope, assuming conditions of clear sky.

The albedo (α) was calculated from the reflectivity data of the bands 1 to 5 and 7 of Landsat (Eq. 3), according to the model proposed by Tasumi et al. (2008):

$$\begin{aligned} \alpha &= 0.254_{\rho 1} + 0.149_{\rho 2} + 0.147_{\rho 3} + \\ &+ 0.311_{\rho 4} + 0.103_{\rho 5} + 0.036_{\rho 7} \end{aligned} \quad (3)$$

where:

ρ_1, ρ_2, ρ_3, ρ_4, ρ_5 and ρ_7 - spectral reflectivity of the bands 1 to 5 and 7 of Landsat 7-ETM+.

Incident longwave radiation was obtained using Eq. 4:

$$R_{atm} = \varepsilon_a \sigma T_{air}^{\ 4} \quad (4)$$

where:

ε_a - atmosphere emissivity;
σ - Stefan-Boltzmann's constant, 5.67 10^{-8} W m^{-2} K^{-4}; and,
T_{air} - air temperature, K.

Atmosphere emissivity was obtained by Eq. 5:

$$\varepsilon_a = 0.85(-\ln \tau_{sw})^{0.09} \quad (5)$$

where:

τ_{sw} - atmospheric transmissivity applying the ASCE-EWRI model (Allen et al., 2007).

Soil heat flux (G) was obtained as a fraction of net radiation (Allen et al., 2007), according to Eqs. 6 and 7:

- For LAI ≥ 0.5:

$$G = \left(0.05 + 0.18e^{-0.52LAI}\right)Rn \quad (6)$$

- For LAI < 0.5:

$$G = 1.8(T_s - 273.15) + 0.084Rn \quad (7)$$

where:

LAI - Leaf area index, m^2 m^{-2};
T_s - Surface temperature (K); and,
Rn - Net radiation (W m^{-2}).

For each pixel, LAI was determined from the SAVI index:

$$LAI = \frac{-\ln\left[\frac{0.69 - SAVI}{0.59} / 0.59\right]}{0.91} \quad (8)$$

where:

SAVI - soil-adjusted vegetation index.

Sensible heat flux (H) was obtained for each pixel using Eq. 9:

$$H = \rho_{air} C_p \frac{\Delta T}{r_{ah}} \quad (9)$$

where:

ρ_{air} - air density, kg m^{-3};
C_p - specific heat at constant pressure, J kg^{-1} K^{-1};
ΔT - temperature difference between two heights close to the surface; and,
r_{ah} - aerodynamic resistance between two heights close to the surface (normally between 0.1 and 2 m) calculated as a function for each pixel.

The parameter r_{ah} was obtained by extrapolating wind speed to 200 m height, at which temperature is independent of H, based on the Monin-Obukhov's theory. ΔT was obtained from the model proposed by Bastiaanssen et al. (1998), who established a linear relationship with the surface temperature present in Eq. 10:

$$\Delta T = b + aT_{s\,datum} \quad (10)$$

where:

a and b - empirical coefficients obtained for each image; and,
$T_{s\,datum}$ - surface temperature adjusted to an elevation in common, using the digital model of the terrain and a vertical temperature gradient.

It is calculated from T_s incorporating all instability effects into the aerodynamic roughness r_{ah}.

The empirical determination of the factors that establish the linear relationship (Eq. 10) is carried out from the selection of two calibration pixels. For the case of "hot" pixel, a pixel must be chosen within the image in which the soil water balance is zero. These "hot" pixels usually correspond to uncovered surfaces with a value of high temperature. To select the "cold" pixel, one must choose a surface with a high degree of cover and good water condition, so that it can be considered with an evapotranspiration 5% higher than ET in a reference alfalfa (1.2 ETo). This pixel usually marks the lowest temperatures in the image and is therefore called a "cold" pixel.

"Cold" and "hot" pixels must conform to the energy balance equation (Eqs. 11 and 12):

- Hot pixel:

$$H_{hot} = (Rn - G)_{hot} \quad (11)$$

- Cold pixel:

$$H_{cold} = (Rn - G)_{cold} - LE_{cold} \quad (12)$$

The ΔT factor was obtained by applying the METRIC model (Allen et al., 2007) in each pixel of the image (Eqs. 13 and 14). All details referring to these calculations can be found in the publication of the METRIC model (Allen et al., 2007).

$$\Delta T_{hot} = \frac{(Rn - G)_{hot} r_{ah\,hot}}{\rho_{air\,hot} C_p} \quad (13)$$

$$\Delta T_{cold} = \frac{(Rn - G - LE)_{cold} r_{ah\,cold}}{\rho_{air\,cold} C_p} \quad (14)$$

The coefficients present in Eq. 10 were obtained as follows:

$$a = \frac{\Delta T_{hot} - \Delta T_{cold}}{T_{s\,hot} - T_{s\,cold}} \quad (15)$$

$$b = \Delta T_{hot} - a T_{s\,hot} \quad (16)$$

The evapotranspiration at the satellite pass time, instantaneous ET (mm h^{-1}), was calculated for each pixel by dividing LE (W m^{-2}) by the latent heat of vaporization, and then multiplied by the factor 3600 to convert from seconds to hourly scales. The ratio ET_{inst}/ETo_{inst} can be considered constant at the satellite pass time, and ETo_{inst} is the reference evapotranspiration at hourly scale (Allen et al., 2007). Thus, crop evapotranspiration at a daily scale (ET_{24H}) is determined as (Eq. 17):

$$ET_{24H} = \frac{ET_{inst}}{ETo_{inst}} ETo_{24H} \quad (17)$$

The STSEB model uses Eq. 18 to obtain the net radiation (Rn) in each pixel:

$$Rn = (1 - \alpha) R_g + \varepsilon_{surf} R_{atm} - \varepsilon_{sup} \sigma T_s^4 \quad (18)$$

where:

R_g - extracted from the data of a meteorological station installed in the area of interest; and,

ε_{surf} - surface emissivity, dimensionless.

Surface emissivity (Eq. 19) was obtained from the model of Valor & Caselles (1996), which allows estimating an emissivity value for each pixel, based on the vegetation cover fraction, P_v, and assuming typical emissivity values for the vegetation, ε_c, and for the soil, ε_s, of 0.985 and 0.960 (Rubio et al., 2003):

$$\varepsilon_{surf} = \varepsilon_c P_v + \varepsilon_s (1 - P_v)(1 - 1.74 P_v) + 1.7372 (1 - P_v) \quad (19)$$

where:

ε_c - vegetation emissivity;

ε_s - soil emissivity; and,

P_v - vegetation cover fraction.

The vegetation cover fraction (P_v), which allows estimating the quantity, quality and development of the vegetation, was estimated using Eq. 20:

$$P_v = \frac{\left(1 - \frac{i}{i_s}\right)}{\left(1 - \frac{i}{i_s}\right) - K\left(1 - \frac{i}{i_v}\right)} \quad (20)$$

where:

i - NDVI of the pixel considered;

i_v and i_s - NDVI values obtained on a vegetated pixel and on an unvegetated pixel; and,

K - obtained by Eq. 21:

$$K = \frac{\rho_{2v} - \rho_{1v}}{\rho_{2s} - \rho_{1s}} \quad (21)$$

where:

ρ_{2v} and ρ_{1v} - reflectivity measured in the vegetation at near infrared and red, respectively; and,

ρ_{2v} and ρ_{1v} - same measurements taken in a pixel of bare soil.

Soil heat flux (G) was obtained as a function of the fraction of the net radiation, according to Eq. 22 (Choudhury et al., 1987):

$$G = C_g (1 - P_v) Rn \quad (22)$$

where a value of 0.275 J kg^{-1} $°C^{-1}$ was assigned to gravimetric specific heat (C_g).

The calculation of the sensible heat flux (H) was performed according to the approach of the two-source model proposed by Sánchez et al. (2011). This model takes into account contributions to the total flux from the soil, H_s, and from the vegetation, H_c, in the following form:

$$H = P_v H_c + (1 - P_v) H_s \quad (23)$$

H_c and H_s were obtained using Eqs. 24 and 25:

$$H_c = \rho C_p \frac{T_c - T_a}{r_a^h} \quad (24)$$

$$H_s = \rho C_p \frac{T_s - T_a}{r_a^a + r_a^s} \quad (25)$$

where:

T_c and T_s - temperatures (K) of the vegetation and soil in the area, respectively;

T_a - air temperature (K); and,

r_a^h, r_a^a and r_a^s - aerodynamic resistances (s m^{-1}) of the canopy, air and soil, respectively.

These aerodynamic resistances were obtained through expressions involving wind speed, u (m s^{-1}) and vegetation height, h (m).

To obtain the daily LE (LE_d), the term G can be neglected (only on a daily scale) and the equation is reduced to the expression: $Rn_d = H_d + LE_d$. Thus, it is possible to extrapolate the instantaneous values to daily values using Eq. 26:

$$LE_d = Rn_d - H_d = \frac{Rn_d}{Rn_i}(Rn_i - H_i) \qquad (26)$$

where:

Rn_d - obtained using the data from a weather station installed in the area of interest, from the measurements of the CNR4 net radiometer (Rn_d/Rn_i ratio varies with time, day of the year and latitude, but not with vegetation type).

The daily ET for the two-source method is finally obtained from the quotient of LE (W m^{-2}) by the latent heat of vaporization and then multiplied by the factor 86400 to convert from seconds to daily scale.

Results and Discussion

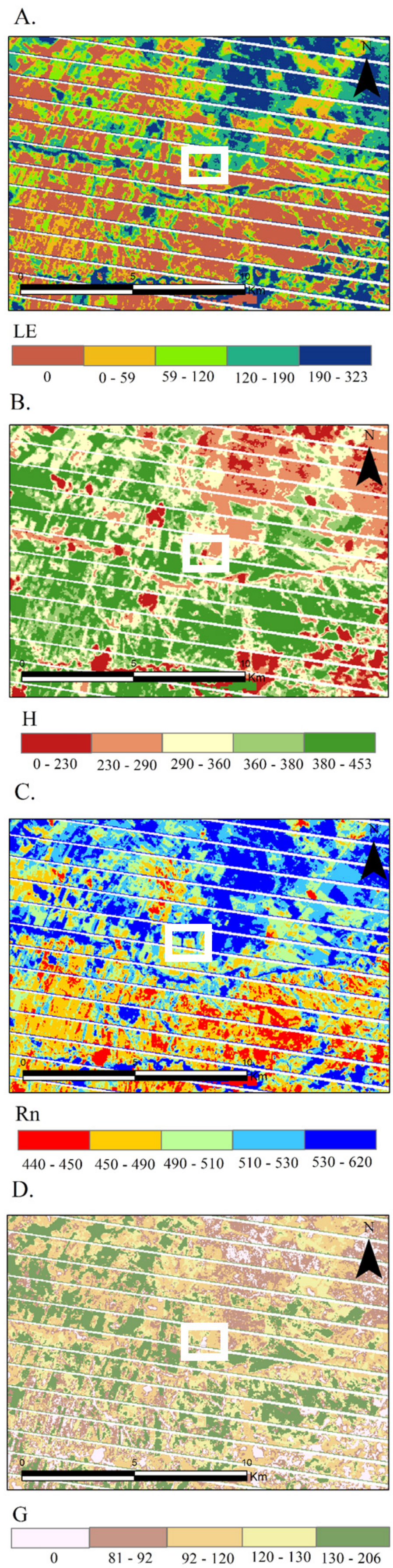
The daily ET and the instantaneous surface energy fluxes LE, Rn, H and G (W m^{-2}) were estimated separately through the METRIC and STSEB models for the sorghum plot. Figure 2 shows an example of the spatial distribution of instantaneous energy fluxes obtained using the METRIC model in the vicinity of the study area, for the date of May 28, 2012.

The modeled values of daily ET and instantaneous fluxes were compared (Figure 3) with the ground-measured data by a net radiometer (Rn), soil heat flux plates (G) and lysimeter (LE).

The comparison with the in-situ measurements of daily ET shows RMSE values of 0.8 mm d^{-1} with METRIC and 0.7 mm d^{-1} with STSEB. These results are similar to those obtained by other authors, such as the error of 0.6 mm d^{-1} in a vineyard using the METRIC model (González-Piqueras et al., 2015) or the error of 0.5 mm d^{-1} obtained by the two-source model (González-Dugo et al., 2012). Results in this study demonstrate the capacity to obtain the ET also in sorghum by satellite.

In terms of instantaneous fluxes, the comparison between the measured and estimated values of Rn resulted in RMSE values of 60 W m^{-2} (METRIC) and 40 W m^{-2} (STSEB). Probably the better agreement of the Rn values with STSEB comes from the use of ground measured values of Rg, whereas METRIC requires an estimation. For LE, RMSE values were 50 and 70 W m^{-2} for METRIC and STSEB, respectively. For H, RMSE values resulted 130 and 120 W m^{-2} for METRIC and STSEB, respectively. For G, the RMSE values of 5 W m^{-2} with METRIC and 21 W m^{-2} with STSEB were obtained. The observed tendency to overestimate G values has also been found in other studies (González-Dugo et al., 2012; González-Piqueras et al., 2015). According to Bastiaanssen (2000), the term G is the one with greatest problem of precision in energy balance models.

Table 1 presents the measurements of the lysimeter and the results with METRIC and STSEB models for each image available.



In the four images, the location of the area is within the white square

Figure 2. Maps of instantaneous energy fluxes (W m^{-2}) in the study area for the Landsat 7-ETM+ image with date of May 28, 2012, obtained with METRIC: (A) latent heat flux, LE, (B) sensible heat flux, H, (C) net radiation, Rn, (D) soil heat flux, G

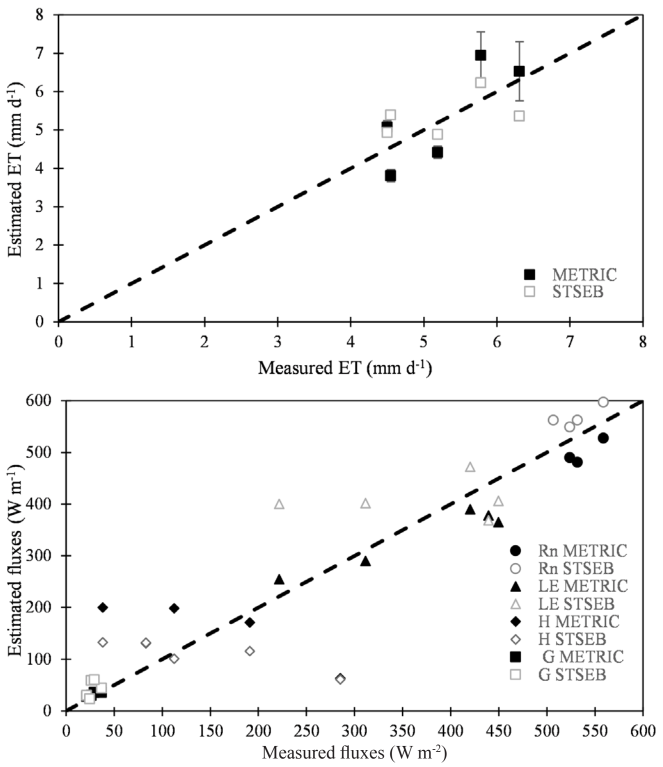


Figure 3. Comparison between the daily ET (A) and the estimated fluxes of latent heat, soil heat and net radiation (B) with the values measured in situ

Table 1. Values of ET (mm d^{-1}) measured with lysimeter and estimated using the METRIC and STSEB method, for the two experiments

Julian Day	ET (Lysimeter)	ET (METRIC)*	Δ METRIC (%)	ET (STSEB)*	Δ STSEB (%)
133	4.5	5.1	13	4.9	9
149	5.2	4.4	-15	4.9	-6
165	4.6	3.8	-17	5.4	17
325	5.8	7.0	21	6.2	7
357	6.3	6.5	3	5.4	-14
Mean	5.7	5.4	-5	5.4	-5

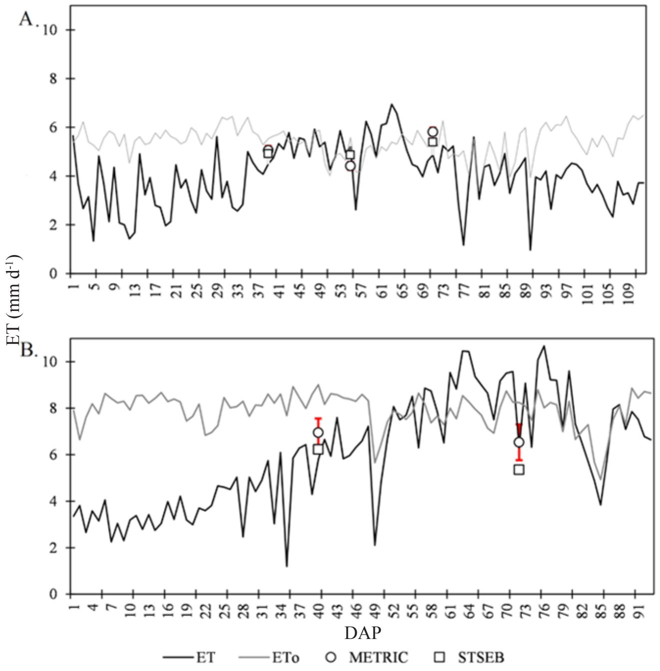
* Mean value of the plot sown with sorghum where the lysimeter was installed

The mean of ET measured in the lysimeter for the days with satellite overpass was 5.7 mm d^{-1}, with a maximum value of 6.3 (JD 357) and a minimum of 4.5 (JD 133). By comparing these data with the values estimated by METRIC and STSEB, it can be noted that both models underestimate only 5%, with an average of 5.4 mm d^{-1} in both cases.

Figure 4 shows the temporal evolution of the evapotranspiration measured in the lysimeter (ET), reference evapotranspiration (ETo) and the ET values estimated by METRIC and STSEB.

In the first experiment (Figure 4A), the values of ET in the lysimeter showed a mean of 4.0 mm d^{-1} with a cumulative total of 452 mm and a mean ETo of 5.4 mm d^{-1}, with a cumulative total of 606 mm.

In the second experiment (Figure 4B), it can be observed that the values of ET and ETo were higher than those of the first experiment, due to the higher evaporation rate in those dates. The mean ET for sorghum in this second experiment was 6.0 mm d^{-1} with an accumulated value of 557 mm throughout the cycle. The mean ETo value was 7.9 mm d^{-1} with total accumulated in this case of 740 mm for the entire cycle.



DAP - days after planting

Figure 4. Temporal monitoring of the evapotranspiration measured by lysimeter (ET), reference evapotranspiration (ETo) and evapotranspiration estimated by one-source (METRIC) and two-source (STSEB) energy balance models. (A) First experiment and (B) Second experiment

Conclusions

1. Daily ET values were modeled with root mean square error (RMSE) values of 0.8 mm d^{-1} with METRIC and 0.7 mm d^{-1} with STSEB. Satisfactory results were also obtained in terms of instantaneous fluxes.

2. There is reliability of the energy balance models METRIC and STSEB for an accurate estimation of crop evapotranspiration in the semi-arid zone of Northeast Brazil, using remote sensing techniques.

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