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PERFORMANCE OF THE SAFER MODEL IN ESTIMATING ACTUAL EVAPOTRANSPIRATION OF WHEAT AND BEAN IRRIGATED CROPS IN THE CENTRAL BRAZILIAN SAVANNAH

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1 ABSTRACT

Meeting the ever-growing demand for food depends tightly on irrigation. In this scenario, it is essential to manage the scarce water resources available and so to understand the spatial and temporal variation of actual evapotranspiration (ETa). In the past decades, models for monitoring and mapping ETa applying remote sensing data were developed and assessed. In this work, the performance of the Simple Algorithm for Evapotranspiration Retrieving (SAFER) for estimating the evapotranspiration of two annual winter irrigated crops in the Cerrado (Brazilians Savannah) was evaluated. Multispectral and thermal images from the sensors ETM+/Landsat 7 and OLI-TIRS/Landsat 8 were used for this purpose. Initially, the model was calibrated for the wheat crop, then this calibration was tested for the bean crop, using Bowen ration ETa data as reference. After calibration, a coefficient of determination (r^2) equal to 0.91 and the root mean square error (RMSE) equal to 0.58 mm d^{-1} were found for the wheat. For the bean, the r^2 was equal to 0.65 and RMSE, equal to 0.77 mm d^{-1}. The results are satisfactory, although they suggest that the model may present an improved performance with specific calibration for each crop and/or region, or adopting calibration in two stages, for lower and higher NDVI values.

Keywords: remote sensing, water resources, irrigation, Cerrado.

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2 RESUMO

O atendimento da demanda crescente por alimentos depende diretamente da irrigação. Neste cenário, o manejo eficiente dos recursos hídricos e o entendimento da variação temporal e espacial da evapotranspiração real das culturas (ETa) é essencial. Nas últimas décadas, modelos para monitoramento e mapeamento da ETa usando dados de sensoriamento remoto foram desenvolvidos. Neste trabalho, a performance do modelo Simple Algorithm for Evapotranspiration Retrieving (SAFER) foi avaliada para estimativa da evapotranspiração de duas culturas anuais irrigadas de inverno, no Cerrado. Para tal, utilizaram-se imagens multiespectrais e termais dos sensores ETM+/Landsat 7 e OLI-TIRS/Landsat 8. Inicialmente, o modelo foi calibrado para o trigo, sendo testado em seguida para o feijão, utilizando como referência dados de ETa obtidos pelo método da razão de Bowen. Após a calibração, o coeficiente de determinação (r^2) encontrado foi igual a 0,91 e a raiz do erro quadrático médio (RMSE) igual a 0,58 mm d^{-1}, para o trigo. Para o feijão, o r^2 foi igual a 0,65 e a RMSE igual a 0,77 mm d^{-1}. Os resultados são satisfatórios, porém, sugerem que uma performance melhor pode ser obtida ao adotar-se uma calibração específica por cultura e/ou região, ou uma calibração em dois estágios, para valores de NVDI baixos e altos.

Palavras-chave: sensoriamento remoto, recursos hídricos, irrigação, Cerrado.

3 INTRODUCTION

The Cerrado biome (Brazilian Savannahs) is the second largest biome in Brazil and the main responsible for the Brazilian grain production (IBGE, 2017). Considering the expected growing world demand for food (FAO, 2015) associated with political and economic factors, the agricultural production is expected to persist increasing in the Cerrado, which should be achieved through sustainable intensification, that is one of the most important strategies to guarantee global food security (STRASSBURG *et al*., 2014; UNITED NATIONS, 2015).

However, the agriculture intensification in the Cerrado depends highly on irrigation, and the irrigation development is likely to intensify the conflicts over water use, especially in this region, where some important watersheds are already facing water shortage issues, and conflicts among the different water users (CAMBRAIA NETO *et al*., 2021).

Wheat (*Triticum aestivum*) and bean (*Phaseolus vulgaris*) are the main winter irrigated crops cultivated in the Cerrado. Due to the precipitation regime in this region, where there are two well-defined seasons: wet (summer) and dry (winter) – when precipitation is almost null –, in order to grow these crops, full irrigation is reacquired (REBOITA *et al*., 2012).

Enhancing planning, management and regulation of water resources use is mandatory in such conditions and, to achieve this goal, it is important to be able to quantify water consumption in irrigated areas (MEKONNEN *et al*., 2020). In other words, understanding the spatial and temporal variation of evapotranspiration, process of transferring water from the surface to the atmosphere, is fundamental for watershed management (GONÇALVES *et al*., 2019).

The use of remote sensing in agricultural and hydrologic studies, boosted by the development of the techniques in this particular area, is a promising alternative for monitoring water resources use, and improving irrigation management (WARREN *et al*., 2014), since actual evapotranspiration (ETa) can be estimated and mapped using models that apply satellite images associated with meteorological data (BASTIAANSSEN *et al*., 2005; ALLEN, TASUMI, and TREZZA, 2007; SENAY, BUDDE, and VERDIN, 2011)

The main advantages of the application of remote sensing for estimating evapotranspiration are the possibility of getting information about actual evapotranspiration without requiring crop or soil data, and the possibility of covering a large area and time period at different scales, according to the different goals, and with a relatively low cost.

There are several models that can be used to estimate evapotranspiration based on remote sensing data, varying with the basic principles adopted and their complexity. As example, some energy balance-based models can be mentioned, such as the Atmosphere-Land Exchange Inverse (ALEXI) (ANDERSON *et al*., 2007); the Surface Energy Balance Algorithm for Land (SEBAL) (BASTIAANSSEN *et al*., 2005); and the Mapping Evapotranspiration at High Resolution with Internalized Calibration (METRIC) (ALLEN, TASUMI, and TREZZA, 2007). There are also some simplified models, such as those based on the relationship between the crop coefficient (Kc) and the Normalized Difference Vegetation Index (NDVI) (KAMBLE, KILIC, and HUBBARD, 2013; AKDIM *et al*., 2014).

The model Simple Algorithm for Evapotranspiration Retrieving (SAFER) (TEIXEIRA, 2010) appears as a more practical solution for obtaining actual evapotranspiration data using orbital sensors images, by relating the ratio between actual evapotranspiration and the reference evapotranspiration with three remote sensing products: surface temperature, albedo and NDVI (TEIXEIRA, 2010; TEIXEIRA *et al*., 2013).

The operational simplicity is one of SAFER's main advantage, in addition to the fact that it does not require the identification of hot or cold pixels, which can be a limitation during the wet period for many regions (TEIXEIRA, 2010; TEIXEIRA *et al*., 2013).

Although SAFER has been successfully applied in some Brazilian regions and shows up as a promising tool for evapotranspiration monitoring (TEIXEIRA, 2010; TEIXEIRA *et al*., 2013), it still needs to be better tested for Cerrado conditions. Also, there are doubts about the model calibration stability.

Therefore, the main objectives of this work were to assess the performance of SAFER model in estimating actual evapotranspiration for the two most important irrigated winter crops in the Cerrado, and to assess the stability of its calibration.

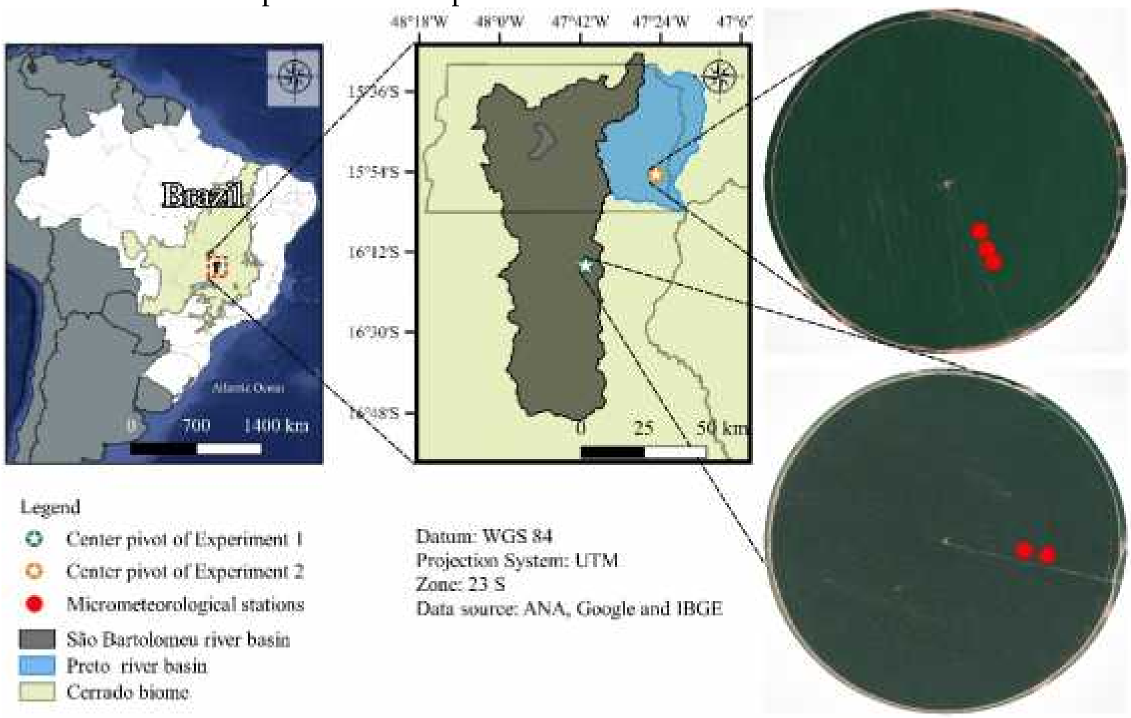
4 MATERIAL AND METHODS

4.1 Study sites and surface energy balance experiments

In order to assess SAFER performance, data from two surface energy balance experiments were used, referring to an irrigated wheat area (Experiment 1 – model calibration) and to an irrigated bean area (Experiment 2 – model evaluation), both in the Cerrado biome, distant from each other approximately 47 km.

In the Experiment 1, on June 27th, 2017, two micrometeorological stations were installed in a 123 ha-center pivot cultivated with wheat, located in the São Bartolomeu River basin (Figure 1). The center pivot geographic coordinates are 16° 15' 8.37" S and 47° 41' 3.67" W and the mean elevation of the center pivot is approximately 983 m above the sea level. The duration of the experiment was 97 days.

Figure 1. Experimental Areas 1 and 2, highlighting the locations of the micrometeorological stations set up in the center pivots cultivated with wheat and bean.



In the Experiment 2, on May 7th and 8th 2015, three micrometeorological stations were installed in a 90 ha-center pivot, cultivated with bean, located in the Preto river basin, in the Federal District (Figure 1). The geographic coordinates of the center of the pivot are 15° 54' 31.20" S and 47° 25' 12.87" W and the mean elevation of the center pivot is approximately 942 m above the sea level. The duration of the experiment was 88 days.

In both experiments, the micrometeorological stations were set up with a minimum fetch of 250 m, respecting the ratio of 100:1 to the upper measurement height as a minimum requirement (STANNARD, 1997).

Average 10 minutes-data collected by each sensor of the micrometeorological stations were recorded in dataloggers (CR3000 Measurement and Control System – Campbell Scientific). The air temperature, relative humidity and the wind speed sensors were set up in two levels. Level 1 was about 1 m above the canopy and level 2, 1 m above level 1. The net radiometer was installed about 2 m above the canopy. Two soil heat flux plates were installed 3 cm deep in the soil. The pluviometer was placed 1.40 m height from the soil surface. The sensors height was adapted to keep the determined distances from the plant canopy, whenever necessary. The specification of the instruments is presented in Table 1.

Table 1. Specification of the instruments installed in the experiments.

Meteorological variable	Instrument specification
Relative Humidity and Temperature Sensor	Model 083E
Wind speed	Met One 014A
Net radiometer	Kipp&Zonen CNR4
Soil heat flux	Model HFP01
Precipitation	TB4 Rain Gage

4.2 Bowen Ratio method

The surface energy balance experiments data were used to obtain the actual evapotranspiration using the Bowen ratio method (ETaBR), adopted as reference to evaluate SAFER performance.

The Bowen ratio method allows to partition the available energy (Rn – G) between sensible heat flux (H) and latent heat flux (LE). LE, in W m^{-2}, and it is calculated by the Equation 1.

$$LE = \frac{Rn - G}{1 + \beta} \quad (1)$$

Where: Rn = net radiation, W m^{-2}; G = soil heat flux, W m^{-2}; and β = Bowen ratio, dimensionless, calculated by the Equation 2.

$$\beta = \gamma \frac{\Delta T}{\Delta e} \quad (2)$$

Where: γ = psychrometric coefficient (0,0626 kPa $°C^{-1}$); ΔT = difference between the temperature, in °C; at levels 1 and 2 (T1 – T2) and Δ*e* = difference between the vapor pressure, in kPa, calculated for the levels 1 and 2 (*e*1 – *e*2).

Actual evapotranspiration (ETaBR), in mm d^{-1}, was calculated by the Equation 3.

$$ETa_{BR} = \frac{t\ LE}{\lambda} \quad (3)$$

Where: λ = water latent heat vaporization, J kg^{-1}; and *t* = time corresponding to the measurement interval, in seconds, equal to 600 s (10 min).

Before ETa calculation, the criteria proposed by PEREZ *et al*. (1999) was applied to the data to remove the improper fluxes. Later, ETa was calculated for the 10-minute period and hourly values were obtained for the daytime (7 a.m. to 6 p.m.) considering the average of the 10-minute data, while ETa was considered equal to zero for the night period. Finally, daily ETa was produced by summing the hourly data.

4.3 SAFER data

The needed meteorological data to run the SAFER model was obtained at the Brazilian National Institute of Meteorology (INMET) and at the Brazilian Agricultural Research Corporation (Embrapa).

For the wheat crop, data from Paranoá Station (OMM: 86733) was used. The station is located about 30 km north from the experimental site, at the elevation of 1043 m above sea level. For the bean crop, data from Embrapa Cerrados station was used. The station is located about 48 km northeast from the experimental site, at the elevation of 1007 m above the sea level.

The remote sensing data was acquired at the Earth Explorer platform of the United States Geological Survey (USGS). We used multispectral and thermal imagens from the sensors ETM+/Landsat 7 and OLI-TIRS/Landsat 8 collection 2 level 1, without cloud contamination for the experimental areas. The path and row of the Landsat images were 221 and 071, respectively. In the experiment 1 (that occurred during 2017 year), the Landsat 7 images dates were June 30, July 17, August 1, August 17, September 2, and September 18 while the Landsat 8 images dates were July 8, July 24, August 9, August 25, September 10, and September 26. In the experiment 2 (2015 year) the Landsat 7 dates were May 24, June 9, July 11, and July 27; and the data of the only Landsat 8 image was July 19.

4.4 SAFER model

The actual evapotranspiration using the SAFER model (ETaSAFER) was calculated by the Equation 4.

$$ETaSAFER = \exp\left[a + b\left(\frac{T_S}{\alpha_0\ NDVI}\right)\right] ETo \quad (4)$$

Where: T_S = surface temperature, °C; α_0 = surface albedo, dimensionless; NDVI = Normalized Difference Vegetation Index (ALLEN, TASUMI, and TREZZA, 2007); ETo = reference evapotranspiration, mm d^{-1}, calculated by the Penman-Monteith-FAO method (ALLEN *et al*., 1998); and a and b = equation coefficients, dimensionless.

The surface albedo was calculated by the Equation 5.

$$\alpha_0 = a_1\, \alpha_p + b_1 \tag{5}$$

Where: αp = planetary albedo (TEIXEIRA, 2010; SILVA *et al*., 2016), dimensionless; and a_1 and b_1 = equation coefficients, equal to 0.70 e 0.06, respectively (TEIXEIRA, 2010).

The surface temperature, in K, was calculated by the Equation 6.

$$T_S = a_2\, T_{sat} + b_2 \tag{6}$$

Where: T_{sat} = brightness temperature at the top of the atmosphere, K; and a_2 and b_2 = equation coefficients, equal to 1,11 e -31,89, respectively (TEIXEIRA, 2010).

The brightness temperature, on its turn, is the temperature of a hypothetical blackbody (that considers the maximum emissivity), in a specific spectral band (band 6 for Landsat 7 and band 10 for Landsat 8), obtained by applying the inverse of the Planck function to the measured radiance:

$$T_{sat} = \frac{K2}{\ln\left(\frac{K1}{L_\lambda} + 1\right)} \tag{7}$$

Where: Lλ = top of the atmosphere spectral radiance for the thermal band, W m^{-2} sr^{-1} μm^{-1}; K1 = band-specific thermal conversion constant from the image metadata, W m^{-2} sr^{-1} μm^{-1}; K2 = band-specific thermal conversion constant from the image metadata, K.

4.5 Calibration and evaluation of the stability of SAFER performance

The model was calibrated by adjusting the coefficients a and b of the Equation (4) using the ETaBR wheat data as reference. Then, the evaluation of the stability of the model performance after calibration was done using the ETaBR with bean data as reference. This approach allowed to verify whether is necessary to calibrate SAFER for each crop.

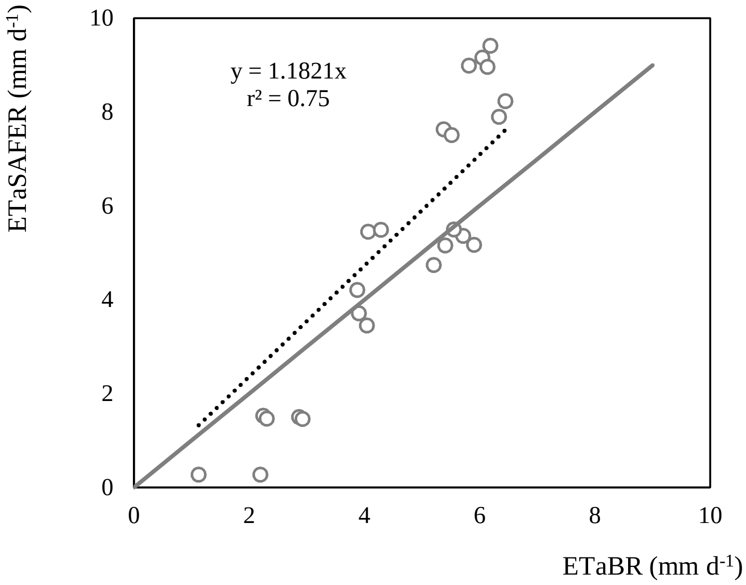
For both cases, the daily ETaBR data referring to the days of satellites overpasses was compared with the mean of the daily ETaSAFER data obtained from the pixels situated inside a circle with 100 m-radius that has the micrometeorological station as the center.

5 RESULTS AND DISCUSSION

5.1 SAFER calibration with the wheat data

Initially, the SAFER performance was evaluated for estimating the wheat actual evapotranspiration on the days of the satellite overpasses using the coefficients a and b proposed by Teixeira (2010), equal to 1.9 and -0.008, respectively, as presented in Figure 2.

Figure 2. Comparison between the wheat actual evapotranspiration estimated by the Simple Algorithm for Evapotranspiration Retrieving (SAFER) model (ETaSAFER) using the coefficients a and b proposed by Teixeira (2010), and by the Bowen ration method (ETaBR).

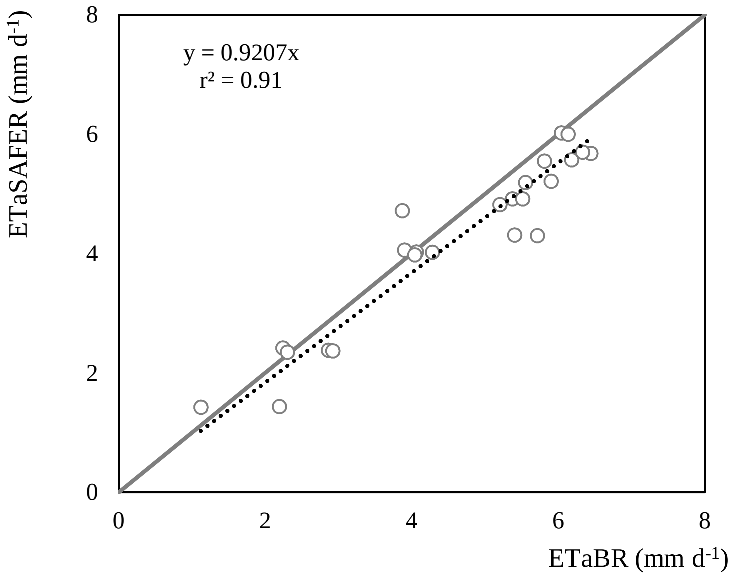


Although the r^2 found, equal to 0.75, was considered good, a strong overestimate was seen for the highest observed values of ETa and a strong underestimate for the lowest observed values. Besides, the RMSE obtained, equal to 1.68 mm d^{-1} was considered unsatisfactory.

Therefore, the model was calibrated (Figure 3) and the result was improved, using the coefficients a = 0.55 and b = -0.0028.

After SAFER calibration (Figures 3), the r^2 increased from 0.75 to 0.91 and the RMSE improved from 1.68 mm d^{-1} to 0.58 mm d^{-1}. The new statistical indicators suggest that the model was properly calibrated.

Figure 3. Comparison between the wheat actual evapotranspiration estimated by the Simple Algorithm for Evapotranspiration Retrieving (SAFER) model (ETaSAFER) after calibration and by the Bowen ration method (ETaBR).

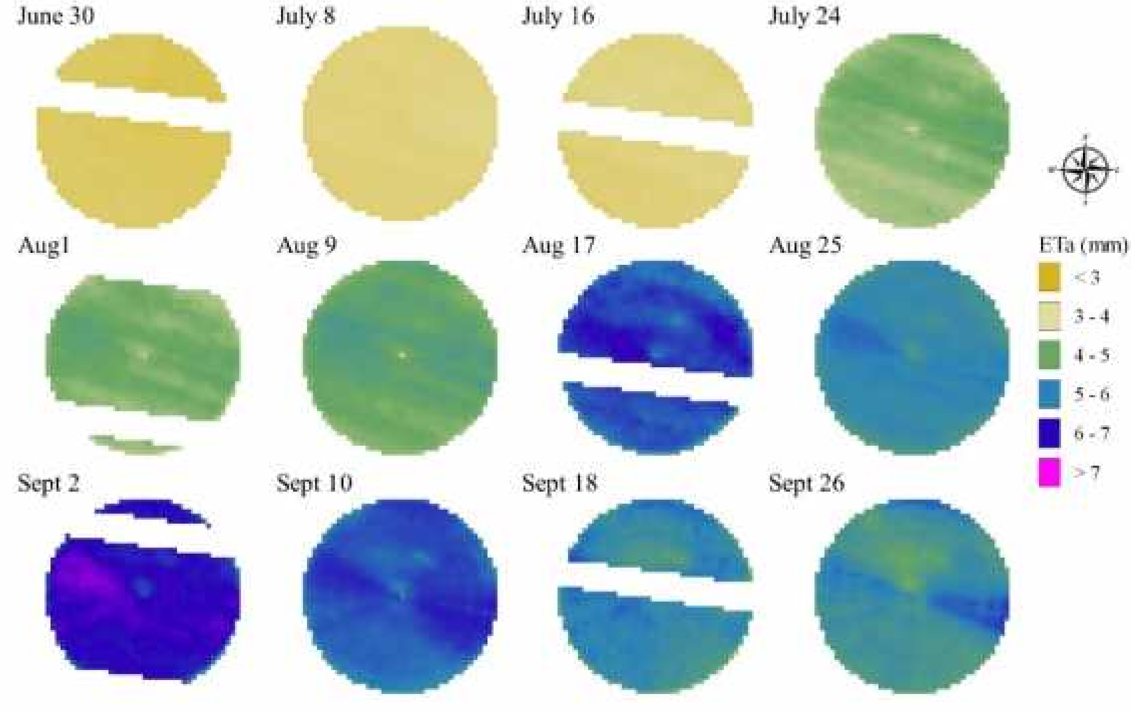


In a study conducted in the Northeast of the State of São Paulo, Teixeira *et al*. (2014) also adopted coefficients calibrated for their study region, using a = 1 and maintaining b = -0.008, as recommended by Teixeira (2010). Franco, Hernandez and Teixeira (2015) and Hernandez, Franco and Teixeira (2015) also used the coefficients a = 1 and b = -0.008 for studies conducted in the Northeast of the State of São Paulo, while Sales *et al*. (2016) used the same coefficients to estimate bean crop evapotranspiration in the *Cerrado* region. On the other hand, Andrade *et al*. (2015) applied the coefficients recommended by Teixeira (2010) for Brazilian semiarid to estimate grass evapotranspiration in the State of Mato Grosso do Sul. Those studies, however, did not assessed the performance of the evapotranspiration estimated by the SAFER model.

5.2 Wheat actual evapotranspiration

The actual evapotranspiration images for the wheat crop obtained using the calibrated model are presented in Figure 4.

Figure 4. Images of wheat actual evapotranspiration (ETa) estimated by the Simple Algorithm for Evapotranspiration Retrieving (SAFER) model.



As expected, the lowest ETaSAFER values were verified at the beginning of the wheat cycle, in the period corresponded to the first three scenes presented in Figure 4, when the vegetation cover was still low (average NDVI for the center pivot equal to 0.22, 0.32 and 0.37, respectively).

An increase on ETaSAFER was observed in the following scenes, as well as an increase in the vegetation cover. On 24 July, 1 August and 9 August, the average NDVI for the center pivot was equal to 0.57, 0.67 and 0.73, respectively. In this period, the crop was in the spike phase and the growth in the vegetative cover was associated to the tillering and the increase in the number of leaves per plant.

Some of the highest ETaSAFER values were observed from 17 August to 2 September (Figure 4), when the crop was going through the stem elongation and heading stages. In the grain filling phase, ETaSAFER started decreasing, as seen in the last two scenes of Figure 4. Due to the highest ETo rates, this decreasing was smooth though.

The SAFER model relates the evapotranspiration to the surface temperature, which is affected by – besides some meteorological parameters such as air temperature and wind speed – soil moisture and the vegetation cover; which in turn are related to the albedo, and to the NDVI. The albedo spatial variation inside the center pivot was small. Analyzing Figure 4 in comparison to Figures 5 and 6, it is possible to observe the model behavior to the variations in NDVI and surface temperature.

Figure 5. Wheat Normalized Difference Vegetation Index (NDVI) images referring to 2017 dates.

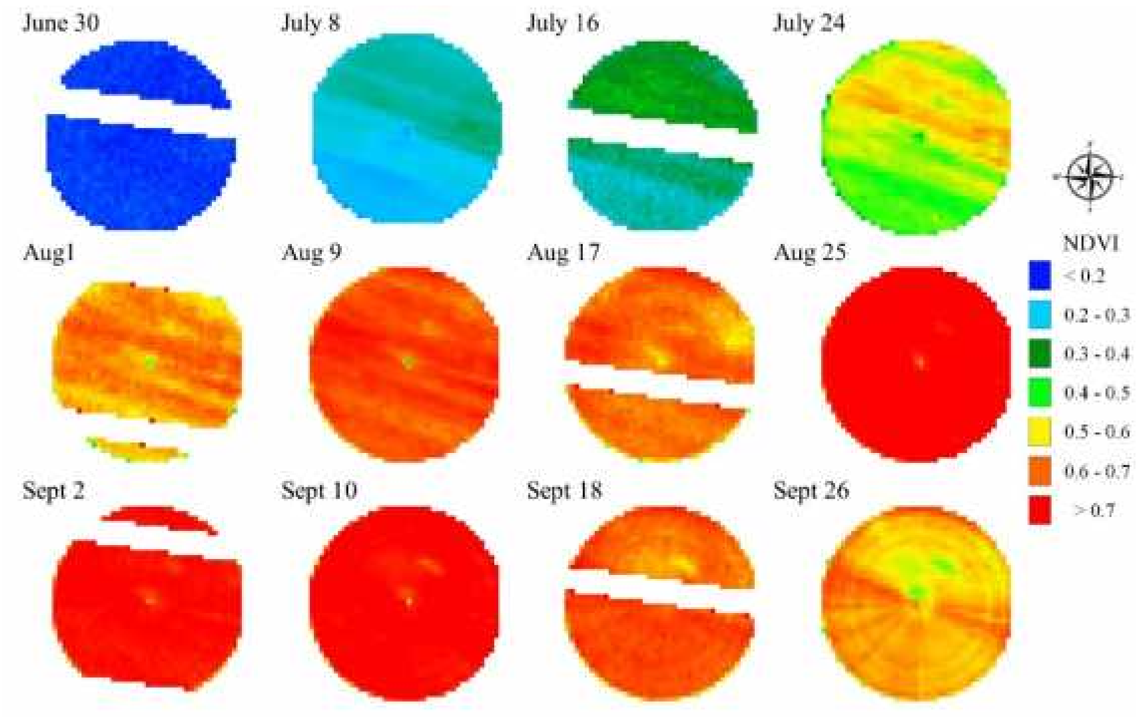
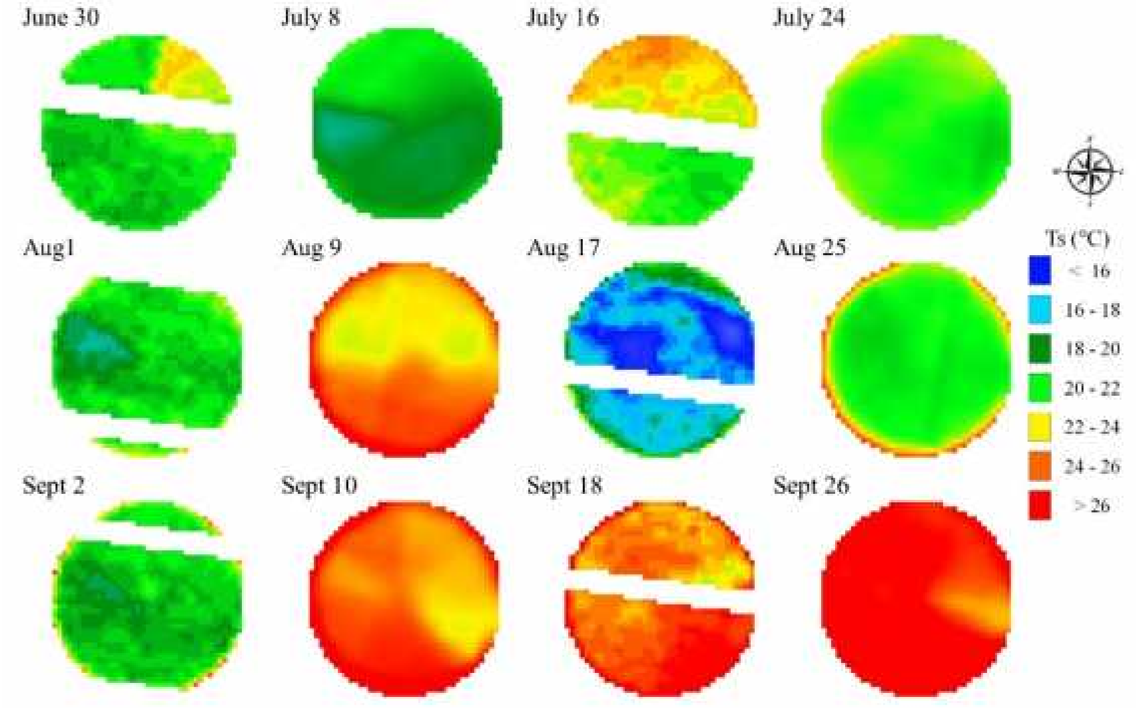


Figure 6. Wheat surface temperature (T_s) images referring to 2017 dates.



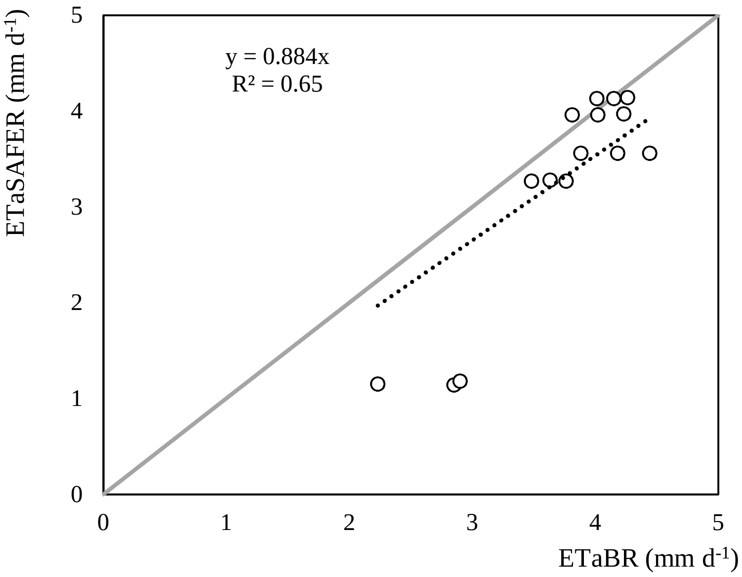
The model response to the NDVI can be seen clearly in the 16 and 24 July scenes. The areas that presented lower NDVI presented also lower ETaSAFER, even though they presented lower surface temperature (Figure 6).

In its turn, the model response to the surface temperature may be seen in the 2 September scene, when a low NDVI variation inside the center pivot was verified (Figure 5). In this scene, the area that presented the lowest surface temperature corresponded to the area with the highest evapotranspiration rates.

5.3 Evaluation of the stability of SAFER calibration using the bean data

The results obtained in the evaluation of SAFER performance with the bean data, using the equation calibrated for the wheat data (a = 0.55 and b = -0.0028), are presented in Figure 7.

Figure 7. Comparison between the bean actual evapotranspiration estimated by the the Simple Algorithm for Evapotranspiration Retrieving (SAFER) model (ETaSAFER) and by the Bowen ration method (ETaBR).



The model performance for the bean crop was inferior to the performance verified for the wheat crop, used for calibrating the model, with r² and RMSE equal to respectively 0.65 and 0.77 mm d^{-1}.

The worst performance occurred in the initial phase of the crop cycle, when the lowest evapotranspiration and NDVI values were observed. The observations suggest that the model may present better performance with a two-stage parametrization, it means, one parametrization for the lower NDVI values and other for the higher ones.

In addition, for being an empirical model, it is recommended calibrating it before using it for a different condition. For being relatively new and little tested, there are doubts about the amplitude of the calibration. The results found in this work may suggest that SAFER would present better performance with more specific calibration for a crop and/or region.

Using remote sensing for estimating the actual evapotranspiration will help to quantify the water consumption for irrigation and will contribute to improve planning, regulation and management of water use. The benefits of using models based on remote sensing, such as SAFER, are evident, since these models allow mapping actual evapotranspiration in large areas, with reasonable spatial resolution and a relatively slow cost.

6 CONCLUSIONS

The SAFER model presented a good performance in estimating evapotranspiration in comparison with the data obtained by the Bowen ratio method, when calibrated for a specific condition.

In the model calibration, using the wheat data, RMSE equal to 0.58 mm d^{-1} and r^2 equal to 0.91 were found. In the model evaluation using bean data and with the same calibration made to the wheat crop, RMSE equal to 0.77 mm d^{-1} and r^2 equal to 0.65 were found.

In general, the results obtained are promising and suggest that the model may present an improved performance with a parametrization in two stages, it means, by defining different parameters for lower and higher NDVI values, or with a more specific parametrization for the region and/or crop.

7 ACKNOWLEDGMENT

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