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ADAPTAÇÃO DO ALGORITMO SAFER PARA IMAGENS LANDSAT 9

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1 RESUMO

O algoritmo SAFER (*Simple Algorithm for Evapotranspiration Retrieving*) tem sido largamente aplicado utilizando imagens obtidas dos satélites MODIS, Sentinel-2 e Landsat-5, 7 e 8. Essa nota científica apresenta a adaptação do algoritmo SAFER para imagens do sensor OLI/Landsat-9, ainda não publicada. Os valores de ET_A estimados pelo método do SAFER apresentaram correlação de Pearson (r) estatisticamente significativo com os métodos FAO 56 e Embrapa (FAO 56, r = 0,96; Embrapa, r = 0,91).

Keywords: necessidade hídrica, imagens de satélite, irrigação

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ADAPTING THE SAFER ALGORITHM FOR LANDSAT 9 IMAGES

2 ABSTRACT

The SAFER algorithm (*Simple Algorithm for Evapotranspiration Retrieving*) has been widely applied to images obtained from the MODIS, Sentinel-2, and Landsat-5, 7, and 8 satellites. This scientific note presents the adaptation of the SAFER algorithm for images from the OLI/Landsat-9 sensor, which has not yet been published. ET_A values estimated via the SAFER method presented a statistically significant Pearson correlation coefficient (r) with the FAO 56 and Embrapa methods (FAO 56, r = 0.96; Embrapa, r = 0.91).

Keywords: water requirements; satellite images; irrigation

3 INTRODUCTION

An efficient water supply through precision irrigation is one way to sustain agriculture with high levels of water productivity. When assessing irrigation performance, it is important to distinguish between the concepts of reference (ET_0), actual (ET_A), and potential (ETp) evapotranspiration, as adopted in this article. ET_0 is considered the water flow from a grassy reference surface with specific characteristics; ET_A represents the water flow considering all environmental conditions; and ETp occurs when the crop is under ideal root zone moisture conditions. ET_A can deviate from ETp because of water stress. In well-irrigated orchards, values of the root zone moisture index, ET_A /ET_0, known as the crop coefficient (Kc), can be used to estimate water requirements, or ETp. The Kc values distinguish crops from standard grassy areas, depending on their phenological stages and climatic conditions.

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On the other hand, in less-than-ideal situations, this index can indicate water stress.

A practical way to implement rational irrigation management is through the Kc-based approach. The values of this coefficient, aimed at improving irrigation management, which were determined through field measurements in Brazil. However, remote sensing with satellite imagery is a powerful alternative for Kc modeling, which has already been applied in various Brazilian agroecosystems via vegetation indices. The upper limit of the ET_A /ET_0 values during a growing season or over the course of a year can be used to fit a representative Kc curve, allowing the estimation of crop water needs and the evaluation of irrigation performance. However, reducing the irrigation depth without compromising productivity is desirable, especially in scenarios of competition for water use between agriculture and other sectors. Several studies have reported water savings while maintaining productivity through water deficit strategies at certain stages of orange tree development, particularly in semiarid regions.

In recent decades, there has been a growing need to accurately estimate the plant water demand in the agricultural sector, which accounts for a large portion of water consumption. Typically, the amount of water consumed by plants is the sum of water evaporated from the soil and transported by vegetation. Traditionally, evapotranspiration is estimated via point models, such as the Penman–Monteith (PM), Priestley–Taylor, Hargreaves, Blaney–Criddle, and crop coefficient-based approaches (Hargreaves; Allen, 2003). However, estimating the spatial distribution of ET over large areas is limited by the low density of meteorological stations. Furthermore, crops present different coefficients throughout phenological stages, which makes it difficult to estimate the crop coefficients and identify development stages in large areas with a great diversity of crops (Allen; Tasumi; Trezza, 2007a; Teixeira *et al.*, 2014; Silva; Teixeira; Manzione, 2019).

Remote sensing algorithms have been developed to quantify the components of the energy and water balance, with different advantages and limitations—such as the SEBAL (Surface Energy Balance Algorithm for Land), S-SEBI, and SEBS (Surface Energy Balance System) algorithms. These models eliminate the need for land use classification, but face limitations in rainy conditions (Foolad *et al.,* 2018), such as the difficulty of identifying a dry pixel (necessary for finding a value where the energy balance finds a static equilibrium) and the requirement for satellite thermal bands (Conrad *et al.,* 2007*).* For operational purposes, the Penman–Monteith equation (Allen, 2008) has been recommended in conjunction with the vegetation indices obtained via remote sensing and agrometeorological data (Allen *et al.,* 2011). The use of this approach, combined with interpolation techniques, is suitable for satellites with low temporal resolution, allowing the analysis of complete agricultural crop cycles (Allen; Tasumi; Trezza, 2007b).

Studies indicate that estimating ET_A based on satellite imagery is essential for the spatial assessment of crop water needs and for rational water use management, especially in regions with limited water resources. Therefore, several remote sensing-based ET models have been developed and tested under different climatic conditions in recent years. Considering the large-scale applicability of the Penman–Monteith equation, the simple algorithm for evapotranspiration retrieval (SAFER) was developed based on field measurements and remote sensing data to estimate the components of the energy and water balance (Teixeira *et al.*, 2014). One of the advantages of SAFER is that it dispenses with both land use classification and hot pixel selection, which are required by other models. In the current version of SAFER, it is possible to estimate the components of the energy and water balance with or without the use of thermal bands, allowing analyses in irrigated areas with a spatial resolution of 30 m via Landsat 8 images (Silva; Teixeira; Manzione, 2019).

Landsat 9 satellite imagery, along with meteorological data from 2024 and 2025, in a study area composed of subbasins with varying land uses in the municipality of Águas de Santa Bárbara, São Paulo state. A key step in this adaptation was obtaining atmospheric correction coefficients at the top of the atmosphere for the different spectral bands of the Landsat-9 OLI sensor, which are essential for calculating albedo.

The results obtained may provide relevant criteria for improving irrigation performance in this region. Furthermore, successful local application may enable the methodology to be replicated in other semiarid environments around the world, possibly requiring only adjustments to the regression coefficients used in the modeling equations.

4 MATERIALS AND METHODS

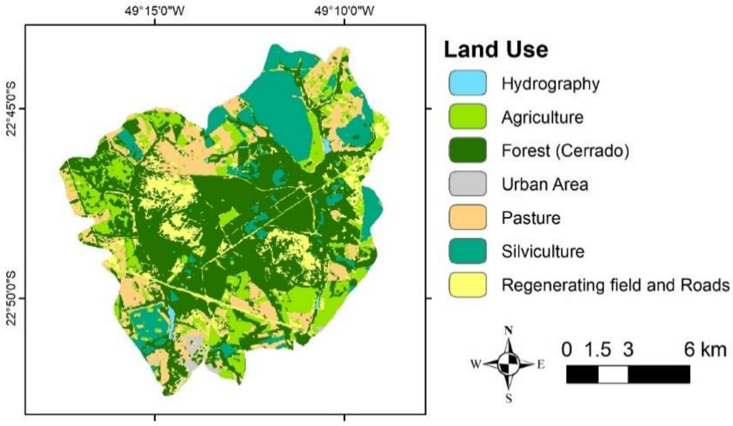
The study area, shown in Figure 1, belongs to the Rio Pardo hydrographic unit, which is part of the Paranapanema River basin, in the Water Resources Management Unit 17 — Médio Paranapanema (UGRHI 17 - MP). The site is bounded to the east by the Capão Rico River and to the west by the Capivari River.

The land use in the study area of this research (based on DOY 75/2017), also presented in Figure 1, is diverse: natural vegetation (Cerrado biome) — 67 km²; forestry (eucalyptus) — 22 km²; sugarcane cultivation — 25 km²; urban area — 2 km²; regeneration fields — 5 km²; roads — 0.4 km²; and pastures — 40 km² (Silva; Manzione; Albuquerque Filho, 2019).

The northern region of the study area is largely occupied by forestry. The western region is used for agriculture (sugarcane), whereas the southern region features urban areas. Pasture and forest areas are concentrated in the central and eastern portions of the study area (Silva; Manzione; Albuquerque Filho, 2018).

The agrometeorological station located in this area has a reference surface with an albedo of 0.23 and a leaf area index (LAI) of 2.88 (Manzione, 2019).

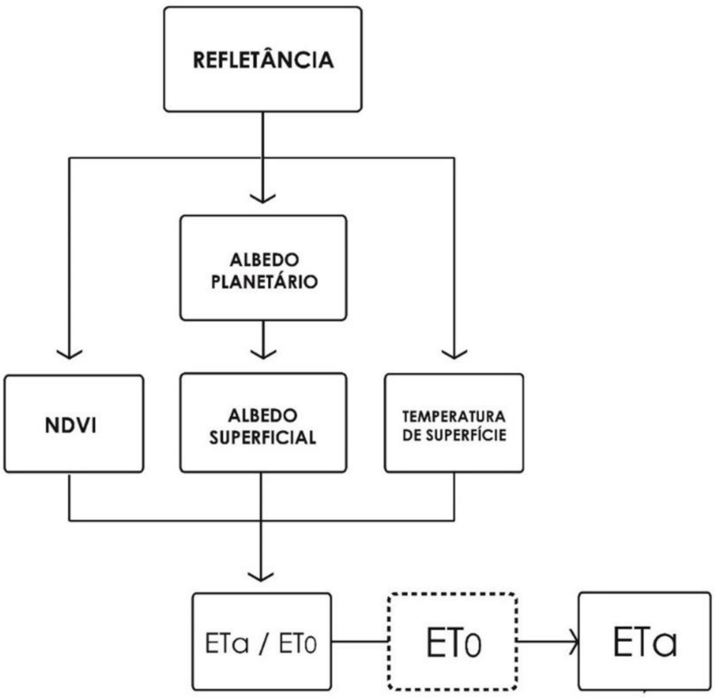
Figure 1. Land use in the study area



Source: Silva, Manzione, and Albuquerque Filho (2019)

Bands 1 to 7 of the Landsat 9 satellite (with a spatial resolution of 30 m) were used to calculate surface albedo (α_0) and the normalized difference vegetation index (NDVI), whereas surface temperature (T_0) was estimated via thermal bands 10 and 11. Figure 2 presents the calculation steps of the SAFER model, in which the boxes with solid lines represent the spatialized variables obtained via remote sensing and the dashed boxes indicate the input data from the agrometeorological station. In this figure, ET_0 refers to the reference evapotranspiration, and ET_A refers to the actual evapotranspiration.

Figure 2. Flowchart for calculating the actual evapotranspiration (ET_A) and evapotranspiration fraction (ET_A/ET_0) via the SAFER model



Source: Silva, Teixeira, and Manzione (2019)

All regression coefficients required for the application of the SAFER algorithm, as described in Figure 2, were previously determined and statistically analyzed in the Brazilian semiarid region based on simultaneous field measurements and Landsat images performed in strongly contrasting agroecosystems over several years. The field data used in the calibration and validation of the model involved sparse irrigated crops and typical natural vegetation of the semiarid region (Caatinga) from 2001--2007. Furthermore, the ET_A /ET_0 values under optimal root zone moisture conditions, in the present study with lemon trees, were compared with the crop coefficients (Kc) available in the literature. Thus, because of these calibrations, validations, and assumptions specific to semi-arid environments, it is possible to expect sufficient accuracy in the estimation of the energy balance, as well as in irrigation performance assessments under the conditions of the study area.

Following Figure 2, the spectral radiances (L_b) of bands (b) 1 to 7 were calculated from their digital numbers (DN_b):

$$L_b = a + bDN_b \quad (1)$$

where L_b is in W m $^{-2}$ sr $^{-1}$ µm $^{-1}$ and where a and b are regression coefficients given in the metadata file.

The Landsat satellite band (ref_b) was calculated as follows:

$$ref_b = \frac{L_b \pi d^2}{R_{a_b} \cos\varphi} \quad (2)$$

where d is the relative Earth–Sun distance; R_{a_b} is the mean solar irradiance on top of the atmospheric irradiance for each band (Wm^{-2} µm $^{-1}$); and φ is the solar zenith angle.

The broadband planetary albedo (α_p) was calculated as the total sum of the reflectance values (ref) for each band from 1-7 (ref_b), according to the weights for each band (w_{band}):

$$\alpha_p = \sum_{b_1}^{b_7} w_{band} ref_b \quad (3)$$

Obtaining adequate w_{band} values for the Landsat-9 satellite is essential for the correct application of the SAFER algorithm, as this corresponds to one of the initial steps of the procedure. Therefore, paying special attention to this phase is a fundamental step for the consolidation and dissemination of the SAFER algorithm in new studies. To estimate surface albedo (α_0), atmospheric corrections were applied to the albedo values at the top of the atmosphere (αp) based on regressions performed from previous field measurements and Landsat imagery. These measurements included irrigated crops and natural vegetation under different climatic conditions in the Brazilian semiarid region. The normalized difference vegetation index (NDVI) was calculated from the reflectances of bands 4 (ref_4) and 5. (ref_5), according to the equation:

$$NDVI = \frac{ref_5 - ref_4}{ref_5 + ref_4} \quad (4)$$

The evapotranspiration ratio, i.e., the ratio between actual evapotranspiration (ET_A) and reference evapotranspiration (ET_0), is estimated as:

$$\frac{ET_A}{ET_0} = exp\left[a_{sf} + b_{sf}\left(\frac{T_0}{\alpha_0 NDVI}\right)\right] \quad (5)$$

where a_{sf} and b_{sf} are regression coefficients, which are 1.8 and − 0.008, respectively, for semiarid Brazil, resulting from simultaneous field and remote sensing measurements of ET_A and ET_0 and α_0, T_0 and NDVI, respectively.

The ET_0 values, which were calculated from meteorological data, were then multiplied by the ET_A/ET_0 values obtained from satellite passes, resulting in large-scale daily values of actual evapotranspiration (ET_A). According to Allen *et al.* (1998), the ratio ET_A / ET_0 can be considered approximately constant throughout the day.

To obtain coherent w_{band} values (Eq. 3) applicable to the SAFER algorithm for different land use types, an optimization study was conducted based on values previously applied to Landsat-8 and Sentinel-2 (Silva; Teixeira; Manzione, 2019). The procedure consisted of incrementally varying the w_{band} values by 0.01 (positive or negative), changing one band at a time. The evaluation of the statistical performance of the evapotranspiration estimate via the SAFER algorithm was carried out since the correlation between the data estimated via remote sensing and those obtained via reference methods, such as those of FAO 56 (Allen *et al.*, 1998) and Embrapa Hortaliças (Marouelli; Silva; Silva, 2008). A linear regression analysis was used, considering Pearson's correlation coefficient (r) and Willmott's index (d). The goodness-of-fit index d Willmott's coefficient, which ranges from 0 to 1, represents the degree of agreement between the estimated values and the observed values and functions as a measure of the model's ability to estimate the dispersion of the data in relation to the observed mean (Willmott *et al.*, 1985).

5 RESULTS AND DISCUSSION

Table 1 presents the relationships among the atmospheric correction weights at the top of the atmosphere (w_{band}) that provided the best results at the end of the SAFER application process. Compared with the coefficients applied in Landsat-8 and Sentinel-2, the values of bands 1 and 3 decreased by 0.01, whereas those of bands 2 and 4 increased by the same proportion.

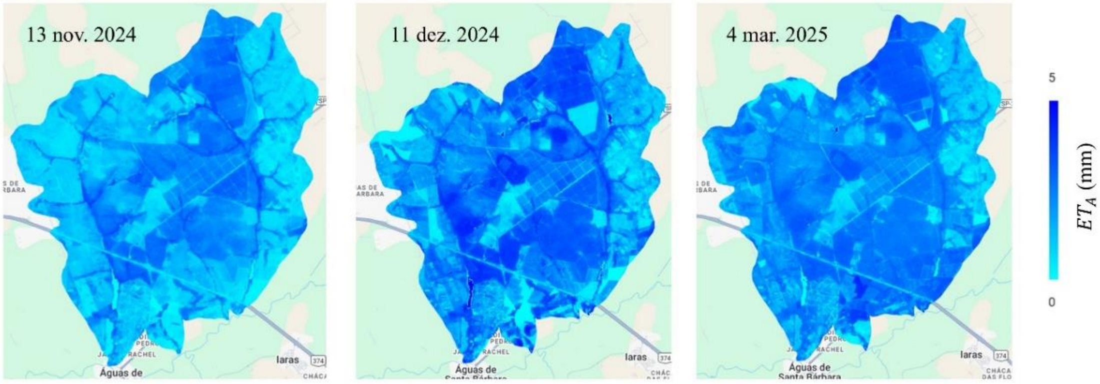
Table 1. Weights for atmospheric correction at the top of the atmosphere (w_{band})for the different spectral bands of the Landsat-9 OLI sensors.

Sensor	Band	w_{band}
Landsat-9 OLI	1	0.11
	2	0.30
	3	0.31
	4	0.12
	5	0.08
	6	0.05
	7	0.04

Source: The authors (2024).

Figure 3 presents the ET_A maps for the study area on November 13 and December 11, 2024, and March 4, 2025. The first date presented lower ET_A values (0.5 to 2.75 mm) due to a drier week, with 25 consecutive days without rain. The second date presented higher ET_A values, a consequence of greater soil water availability, as did the third sampling day, which occurred after 2 and 4 days without rain, respectively. One of the benefits of using SAFER is the model's sensitivity to soil water availability, which is implicit in its formulation (Silva; Teixeira; Manzione, 2019).

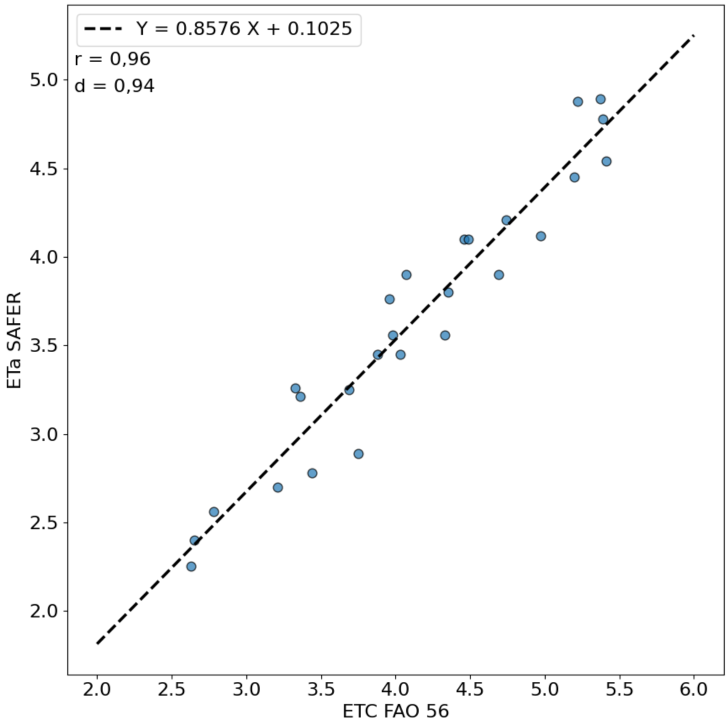
Figure 3. ET_A maps by the SAFER model obtained from images corrected with values considered optimal for atmospheric correction in the context of evapotranspiration modeling



Source: The authors (2024).

For the comparison of ETc estimated via the FAO 56 standard method, the regression curve that best fit the data (Figure 4) was linear, with a Pearson correlation coefficient of 0.96 and a Willmott index of 0.94.

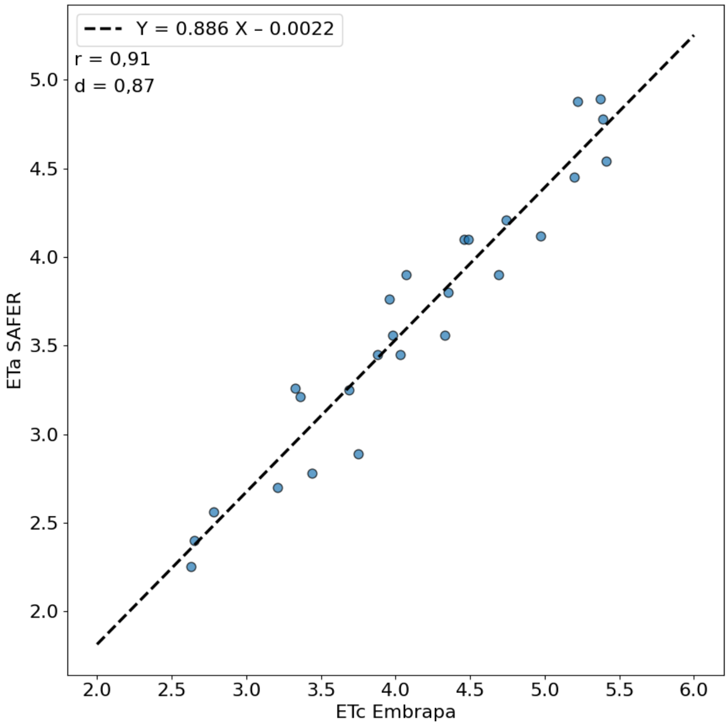
Figure 4. Comparison between ETc estimated via the FAO-56 standard method (Allen *et al.*, 1998) and ET_A via the SAFER method



Source: The authors (2024).

In the ETc estimation method from the Embrapa publication (Figure 5), the Willmott index d was 0.87, whereas the Pearson correlation coefficient r was 0.91. These results indicate a good fit between the methods and demonstrate a strong correlation between the variables analyzed.

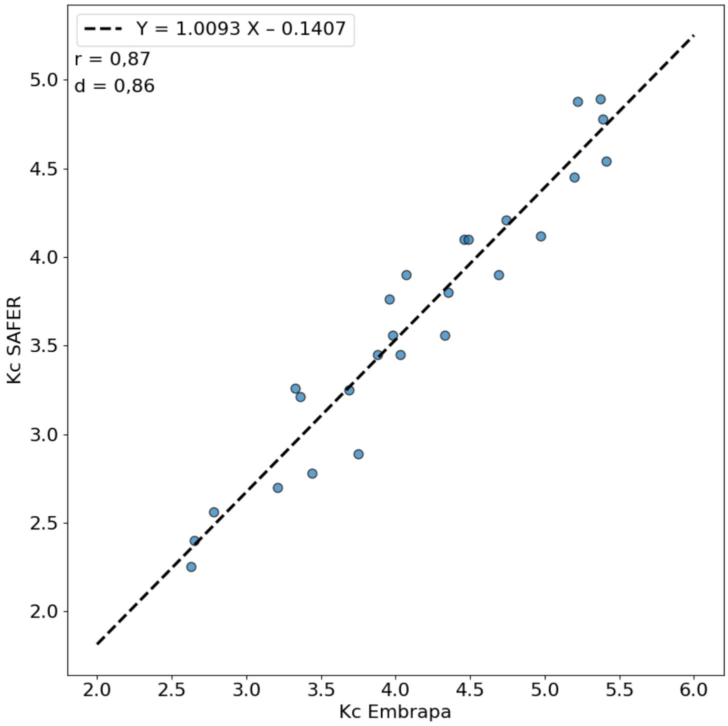
Figure 5. Comparison between the ETc estimated via the standard Embrapa method (Marouelli; Silva; Silva, 2008) and the ET_A via the SAFER method



Source: The authors (2024).

Compared with the crop coefficient (Kc) (Figure 6), the Willmott index d presented a value of 0.86, and the Pearson correlation coefficient r was 0.87, indicating a satisfactory fit, considering the independence of the input variables of the compared methods.

Figure 6. Comparison between Kc estimated via the FAO-56 standard method (Allen *et al.*, 1998) and the evapotranspiration fraction via the SAFER method



Source: The authors (2024).

6 FINAL CONSIDERATIONS

The adaptation of the coefficients for atmospheric correction at the top of the atmosphere for the different spectral bands of the Landsat-9 OLI sensors, the initial step for the application of the SAFER algorithm, was satisfactory since the ET_A and Kc values estimated by SAFER presented a significant correlation with the FAO and Embrapa methods, maintaining coherence with plausible values applicable to irrigation management.

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