Agricultural Water Management 271 (2022) 107763

Contents lists available at ScienceDirect

Agricultural Water Management

journal homepage: www.elsevier.com/locate/agwat

Remote sensing based evapotranspiration modeling for sugarcane in Brazil using a hybrid approach

R.C. Bispo [a,*], F.B.T. Hernandez [a], I.Z. Gonçalves [b,c], C.M.U. Neale [c], A.H.C. Teixeira [d]

[a] São Paulo State University – UNESP, Brazil
[b] University of São Paulo – USP/ESALQ, Brazil
[c] University of Nebraska, Daugherty Water for Food Global Institute, United States
[d] Federal University of Sergipe, Brazil

ARTICLE INFO

Handling editor - Dr Z Xiying

Keywords:
Satellite image
SETMI
Irrigation management
Saccharum officinarum

ABSTRACT

The increasing pressure on water resources in agricultural areas requires the implementation of innovative tools and solutions to improve irrigation water management. Against that background, this research presents the application of a remote sensing-based methodology for estimating actual evapotranspiration (ETa) based on two-source energy balance model (TSEB) and remote sensing-water balance (RSWB) coupling for sugarcane crop in Brazil using the hybrid model Spatial EvapoTranspiration Modeling Interface (SETMI). Estimated results through SETMI and field data using the eddy covariance system (EC) considering two growing seasons were used to validate the energy balance components and ETa. In addition, the basal crop coefficient as a function of the spectral reflectance (Kcbrf) was developed through the soil-adjusted vegetation index (SAVI) and observed ET. Modeled energy balance components showed a strong correlation to the ground data from EC, with ET presenting R^2 equal to 0.94 and a Pearson correlation coefficient (ρ) equal to 0.88. Regarding Kcbrf, the Kcb-SAVI relationship for sugarcane presented a high correlation with an R^2 value of 0.85 and an "ρ" equal to 0.92. On average, considering the whole season, Kcb was equal to 0.75 and 0.73 for the 4th ratoon and 5th ratoon, respectively. Overall, the average Kc throughout the period was 0.73 and 0.70 for the 4th and 5th ratoons respectively, and the maximum Kc of about 1.23 for both growing seasons. On average, accumulated ETa presented 1025 mm resulting in ETa rates of 2.9 mm per day considering the two seasons. Crop water productivity (WP) obtained values similar between the seasons, averaging 12.6, 21.7, and 12.3 kg m^{-3} for WPp+i, WPi and $WP_{ET,}$ respectively. The SETMI hybrid model produced suitable estimated daily ETa values over the two growing seasons through remote sensing based on the Kcb-SAVI relationship and good performance of TSEB model during the evaluated growing periods confirming the applicability of the model under tropical conditions in Brazil focusing on improving irrigation management in sugarcane crop.

1. Introduction

Brazil expects to harvest about 10 million hectares of sugarcane for the 2020/2021 season, which corresponds to 665 million metric tons, establishing the world's largest producer of sugarcane. The State of São Paulo is the main contributor with an estimated production of more than 360 million tons total. The main products derived from sugarcane are biofuel and sugar, with 30 billion liters of ethanol and almost 42 million tons of sugar estimated for the next harvest. These numbers could be even higher, given that most of the cultivated areas are under rainfed conditions which can negatively impact sugarcane productivity in Brazil. Productivity is much lower than that achieved in irrigated areas, approximately 69 t ha^{-1}, due to water stress that can occur in critical stages of crop development (CONAB, 2021). Due to the poor distribution of rain over the long sugarcane growing season (one year each season), the crop is exposed to rainy months and very dry months during its development. As a result, the expansion of the irrigated sugarcane area in Brazil has increased rapidly due to gains in stalk yield (ANA, 2020). Many studies carried out in Brazil have demonstrated that irrigation increases the productivity of sugarcane (Gonçalves et al., 2019, 2013).

The optimization of water use in irrigated agriculture has an important role in the economy, production of food, and environmental security to guarantee the profitability of agricultural activity, and the sustainability of water resources. This is especially important in regions

* Corresponding author.
E-mail address: regianecarvalhoks@gmail.com (R.C. Bispo).

https://doi.org/10.1016/j.agwat.2022.107763
Received 22 February 2022; Received in revised form 4 May 2022; Accepted 2 June 2022

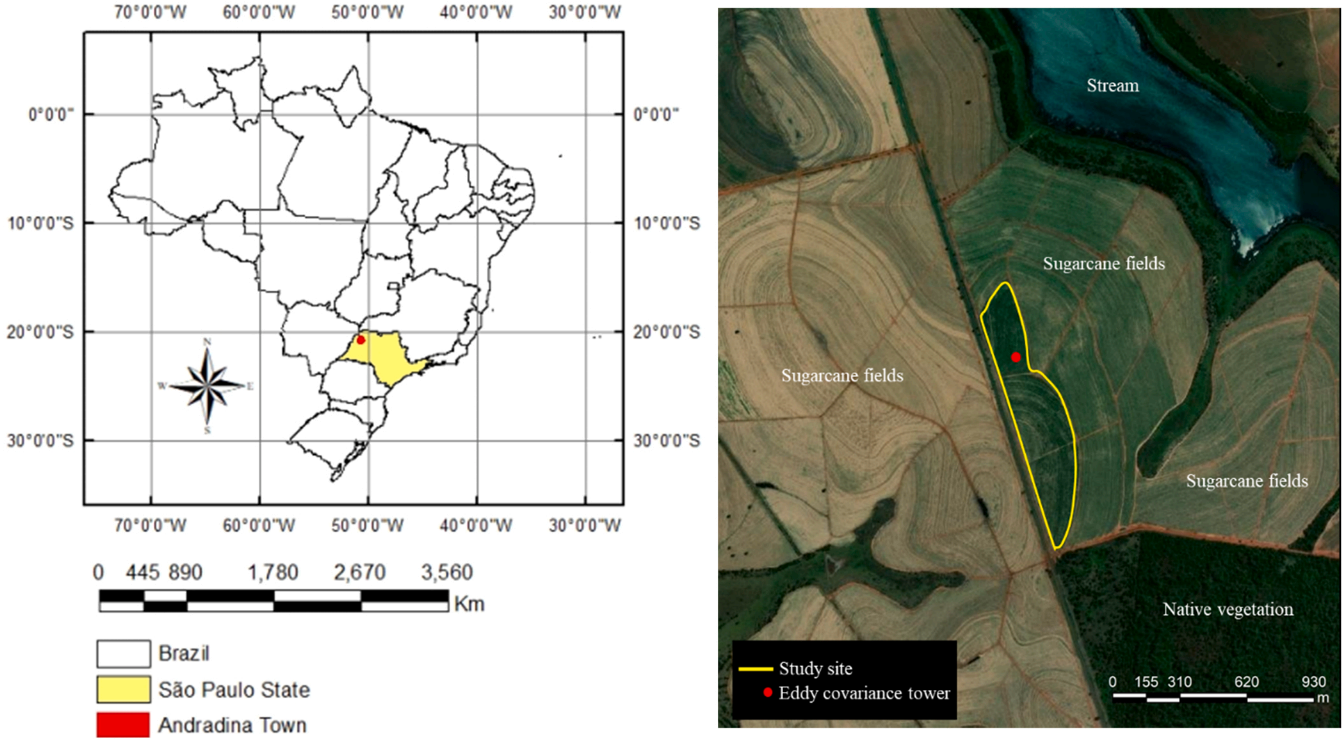

Fig. 1. Location of the study site in Andradina, State of São Paulo - Brazil (left) and, sugarcane field and surroundings (right).

that face water scarcity, as is the case of sugarcane areas in the State of São Paulo. Considering that the use of irrigation is becoming more prevalent for sugarcane production, more efficient and low-cost methods to estimate crop evapotranspiration are important to ensure the proper estimation of the irrigation depth, including models that provide suitable monitoring of water in the root system and crop development in sugarcane irrigated areas.

Evapotranspiration (ET) estimation, based on remote sensing methods using satellite data, has been used widely due to low cost/low impact techniques, high temporal, and spatial resolution sensors that can be used at field scales, as well as global scales, in agricultural systems both in Brazil and worldwide. Recent works such as Venancio et al. (2019), Foster et al. (2019), Gonçalves et al. (2020), and Campos et al. (2018) demonstrated how remote sensing (RS) can be used for the monitoring and management of water resources in irrigated agriculture.

Some RS-based methodologies for estimating ET are based on the energy balance approach using radiometric land surface temperature and meteorological variables to estimate ET as a residual surface energy balance component (SEB) and, these models can be one source when ET is estimated for soil and vegetation together as a single layer such as the well-known SEBAL (Bastiaanssen et al., 1998) and METRIC (Allen and Wright, 1997), and two sources when ET is estimated for soil and vegetation individually such as the Two Source Energy Balance (TSEB) by Norman et al. (1995), and ALEX-DisALEX model (Anderson et al., 1997; Mecikalski, and Norman et al., 1999, 2003). These models use orbital imagery, and ground-based meteorological data and, depending on the model, also can use field data to estimate the components of the energy balance (net radiation, sensitive heat, and soil heat flux) and as a result, obtain latent heat flux or ET.

There are other methods to estimate ET based on the basal crop coefficient as a function of the spectral reflectance values (Kcbrf) derived from vegetation indexes (VI) such as NDVI (Normalized difference Vegetation Index) and SAVI (Soil Adjusted Vegetation Index). The Kcbrf values are used in determining the actual crop ET used to estimate the remote sensing-based soil water balance (RSWB), as described in FAO 56 (Allen et al., 1998). The Kcbrf approach (Neale et al., 1989) has been widely applied to several crops (Campos et al., 2016, 2017, 2021). Also, new biophysical photosynthesis model based on RS such as STIC-RCEEP, integrating land surface temperature (T_R)-based ET or latent heat flux (LE) into a Remote sensing-driven approach to coupling Ecosystem Evapotranspiration and Photosynthesis (RCEEP) model, advantages of STIC-RCEEP are prominent under dry conditions (Bai et al., 2022).

In this research, the hybrid model known as Spatial EvapoTranspiration Modeling Interface (SETMI) (Geli and Neale, 2012; Neale et al., 2012) was applied. The modeling approach is based on coupling the TSEB and Kcbrf approaches. The TSEB model provides estimates of actual crop ET while the Kcbrf (from SAVI corresponding to the time of the satellite overpass) approach allows for updating the basal crop coefficient as well as the interpolation and extrapolation of ET between satellite image acquisition dates, improving the maintenance of a soil water balance in the crop root zone. Additionally, SETMI considers three layers in the soil profile to estimate the RSWB considering the soil heterogeneity pixel by pixel, still, it allows to upload of the climatic input data as tables or raster grid format. Also, the variables such as the variables ET extrapolation, initial canopy temperature, wind adjustment methods, green fraction, canopy height, effective precipitation, basal crop coefficient progression and interpolation can be estimated using more than one method to meet different user needs to run the TSEB and RSWB in the SETMI. Also, SETMI has the ability to provide prescription irrigation maps from ET estimated based on the Kcbrf- water balance allowing temporal interpolation and extrapolation of a spatial water balance between input image dates, this approach has the potential to be used for real-time irrigation scheduling as described in Barker et al. (2018).

The Kcb-VI relationship for sugarcane under Brazilian tropical climate has not been developed yet, therefore, for the proper estimation of ET and RSWB for sugarcane using the SETMI hybrid model, it is necessary to develop a specific Kcb-VI relationship for sugarcane in such conditions. This research proposes to develop a Kcb-VI relationship through Kcb measured in the field with an eddy covariance flux tower and the SAVI vegetation index from satellite imagery for sugarcane

Table 1
Physical characteristics of the soil profile up to 0.60 m deep for the study site.

Layer (m)	Sand (%)	Silt (%)	Clay (%)	[1]BD (g cm^{-3})	Porosity (%)	[2]TAW (mm cm^{-1})
0–0.20	76.4	10.6	13.0	1.60	34.0	1.20
0.20–0.40	75.6	8.40	16.0	1.64	32.3	1.30
0.40–0.60	72.8	7.10	20.1	1.58	35.6	1.20
Average	74.9	8.7	16.4	1.61	34.0	1.23

1BD: bulk density; 2TAW: total available water.

grown in northwest state of Sao Paulo, Brazil. Additionally, after adjusting the model, the objective of this research also was to evaluate the performance results of the estimated energy balance (EB) components and ET using SETMI against field data obtained from the turbulent flux data (eddy covariance). After establishing the Kcb-VI relationship and validating TSEB from SETMI, the hybrid model was applied to estimate daily Kcb, Kc and water balance in the root zone focusing on monitoring the crop growth and irrigation management over two sugarcane seasons in Brazil.

2. Material and methods

2.1. Study site

The research was carried out in a commercial field of 24 ha, close to Andradina, State of São Paulo, Latitude 20°43'43.6″ S, Longitude 51°16'30.3″ W, 360 m of altitude (Fig. 1), grown with sugarcane for two ratoon seasons, fourth and fifth harvesting seasons respectively (June, 2016 to June, 2018) with the variety RB96–6928.

According to the Koppen classification, the climate of the region is defined as tropical type (Aw) with dry winter and rainy summer (Peel et al., 2007), with average annual precipitation of 1242 mm, average annual reference evapotranspiration of 1536 mm, average solar radiation of 17.2 MJ m^{-2} day^{-1}, average air temperature of 23.3 °C, and average relative humidity of 62.4% (UNESP, 2019). The soil is classified as Typical Dystrophic Red Latosol (Santos et al., 2018) and the physical characteristics are shown in Table 1, soil profile layers from 0 to 0.60 m.

The meteorological data used were collected from the Itapura weather station which is part of the Northwestern São Paulo Network (http://clima.feis.unesp.br), 150 m from the study site, EC installed in the field provided the precipitation data. Through the meteorological data, the reference evapotranspiration (ETo) was estimated using the FAO-56 equation (Allen et al., 1998).

Planting was done in September 2013 (first harvest) with singles rows spaced 0.9 m apart and 1.5 m between double rows. The crop was irrigated using a subsurface drip irrigation system with the drip tapes buried at 0.40 m depth, suppling a flow rate of 1 L $hour^{-1}$ per dripper with drippers spaced 0.6 m apart.

2.2. Evapotranspiration measurement - eddy covariance method

An eddy covariance flux tower was installed in the field to measure the micrometeorological variables and the energy balance components for estimating evapotranspiration. The EC consists of a three-dimensional sonic anemometer and an infrared gas analyzer - IRGASON (Campbell Scientific, Logan, Utah, USA), positioned considering the prevailing wind direction, operated by data logger (CR 3000, Campbell Scientific Instruments, Utah, USA) to record raw high-frequency data at 10 Hz measured at 8.0 m above the ground surface.

The micrometeorological variables measured above the canopy were net radiation (CNR4, Net radiometer - Kipp & Zonen, Delft, Netherlands) and precipitation (CS700-L, Hydrological Services Pty. Ltd., Sydney, Australia). This equipment was fixed at 5.0 m above the soil surface. On the ground, heat flux plates were installed to measure the heat flow in the soil (HFP01-L, Campbell Scientific, Inc. Logan, Utah, USA), the data were collected continuously at 5-second intervals averaged over 30 min.

The raw data from the EC system (10 Hz) were processed using *EddyPro Advanced software* (LICOR, 2020a) and *Tovi software* (LICOR, 2020b) was used for data gap filling and flow partitioning every 30 min.

The Bowen Ratio with the flux tower data was used to adjust λE and H by forcing the closure following the procedure suggested by Twine et al. (2000), the flux data obtained showed an energy balance closure on a daily scale of about 71% and 82% for the 4th and 5th ratoon, on average 77%, more details in Bispo (2020). In some cases, this allows a considerable amount of available energy (Rn - G) not counted in the partitioning of latent and sensitive heat flux (λE + H), which could cause significant discrepancies in the comparisons with the results from remote sensing. The errors inherent in Rn (net radiation), λE (latent heat flux), H (sensitive heat flux), and G (heat flux in the soil) are reported as 5–10%, 15–20%, 15–20%, and 20–30%, respectively, according to Weaver (1990) and Field et al. (1994). After closure, the λE values that represent the energy per unit area and per unit time were converted into

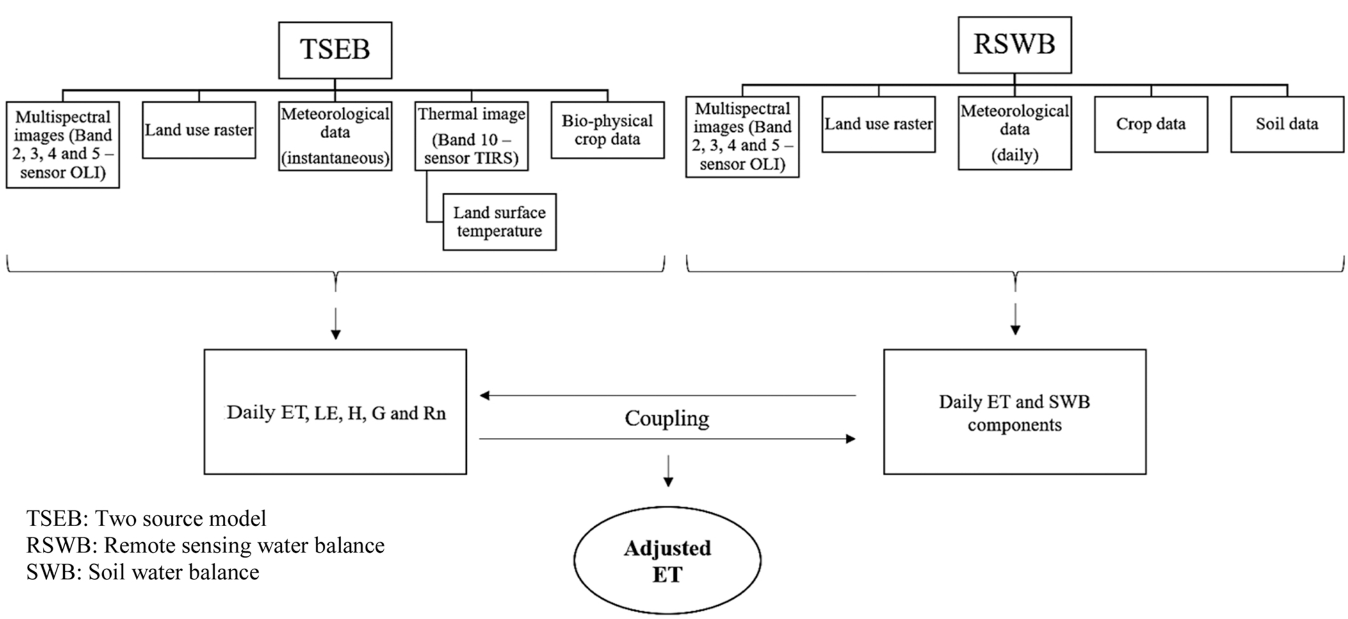

Fig. 2. Flowchart showing how evapotranspiration (ET) was estimated using the SETMI hybrid model.

evapotranspired depth unit for each time interval, resulting in actual evapotranspiration (ETa).

2.3. Spatial EvapoTranspiration Modeling Interface - SETMI

SETMI is the interface through which the hybrid ETa estimation model by Neale et al. (2012) is currently operated. The hybrid model is the combination of the ETa model based on TSEB (Norman et al., 1995) with the RSWB model that uses crop coefficients based on spectral reflectance. In the TSEB, the soil and plant contributions to energy fluxes are considered separately rather than as a combined surface (hence two sources), following the general Eq. 1.

$$(Rn_c + RN_s) = (H_c + H_s) + (LE_c + LE_s) + G \quad (1)$$

Rn: net radiation (w m^{-2}).
H: sensible heat flux (w m^{-2}).
LE: latent heat flux (w m^{-2}).
Subscripts *C* and *S* indicate canopy and soil, respectively.

Instantaneous latent heat flux (LE) computed using the TSEB was scaled to a daily actual ET value following Chávez et al. (2008) using the ratio of instantaneous and daily reference ET according Eq. 2.

$$ET_d = LE_i \quad x \quad \left(\frac{3600}{\lambda}\right) \quad x \quad \left(\frac{ET_{o,d}}{ET_{o,i}}\right) \quad (2)$$

ET_d: actual evapotranspiration (mm per day).
ET_o: reference evapotranspiration (mm).
LE: latent heat flux (w m^{-2}).
λ: latent heat of vaporation (w m^{-2}), Ham (2005).
Subscripts *d* and *i* are for daily and instantaneous values, respectively.

Kcbrf allows the soil water balance to be calculated with a daily time interval when images are less frequent depending on the sensor used (Allen et al., 1998). The inclusion of the hybrid model provides an error verification of the root zone soil water balance (0.60–0.80 m depth for sugarcane root system in this study based on field data), producing a second more adequate ETa estimate (Neale et al., 2012). Thus, it is very important that the TSEB and the water balance in the root zone based on the Kcb-VI relationship are effectively calibrated for the study region. Fig. 2 shows briefly how the ET adjustment is performed in the SETMI hybrid model through TSEB TSEB: Two source model.
RSWB: Remote sensing water balance.
SWB: Soil water balance.
and RSWB coupling.

The RSWB applied in this study does not differ from previously published approaches for other crops (Campos et al., 2016). The methodology is essentially the soil water balance proposed in FAO 56, with additions to simulate the evaporation of the soil top layer according to the percentage of biomass residues on the soil surface, and assimilates the temporal evolution of the Kcb derived from the vegetation index. The SETMI hybrid approach considers the ET obtained from the two-source energy balance model to produce an assimilated value for adjusting the water balance in the root system (Geli and Neale, 2012; Neale et al., 2012), according Eq. 3.

$$ET^A_{WB} = ET^B_{WB} + W \quad x \quad (ET_{TSEB} - ET^B_{WB}) \quad (3)$$

ET^A_{WB}: water balance ET after including the TSEB-ET (ET_{TSEB}) (mm per day).
ET^B_{WB}: water balance ET before the incorporation (mm per day).
W: Kalman gain, computed using the error variance of the water balance and TSEB-ET following (Neale et al., 2012).

After incorporating, RSWB within SETMI considers the daily root growth of the plants and soil physical data of three individual layers along its profile to increase the accuracy of the results. For details on RSWB applying SETMI, the reader is advised to see Barker (2017). SCS Runoff equation developed by the U.S. Soil Conservation Service (USDA-NRCS, 2004) was used to estimate the effective precipitation (Peff) available in the SETMI model.

A Kcb-VI relationship was developed for sugarcane based on the climatic conditions of the region and the remote sensing approach. For this purpose, SAVI (Huete, 1988) was estimated according to Eq. 4 using cloud-free images corrected for surface reflectance with the OLI sensor (Landsat 8 - level 2) considering two sugarcane ratoons (2016–2017 and 2017–2018), total of 21 images used. The images were obtained through an online platform of the USGS (glovis.usgs.gov/app?fullscreen=1), we used “pixel_qa band” to avoid cloud or haze conditions and guarantee pixel quality on the study site.

$$SAVI = \frac{NIR + RED}{NIR - RED + L} * (1 + L) \quad (4)$$

SAVI: soil adjusted vegetation index.
NIR: reflectance value of the near red band (0.845–0.885 μm; 30 m resolution).
RED: reflectance value of the red band (0.630–0.680 μm; 30 m resolution).
L: Soil cover coefficient by green vegetation, value = 0.5.

SAVI is an index designed to mitigate changing soil background effects on analyzed images if the land surface is not fully covered by vegetation, highly recommended in irrigated areas with row crops (Neale et al., 2021). The SAVI values were calculated pixel by pixel and an average was estimated for the whole field, using a vector layer shapefile with a buffer of − 20 m from the edge to avoid border effects. Kcb was measured using data from the EC system, using Eq. 5.

$$Kc = Kcb + Ke = \frac{ET_a}{ET_o} \quad (5)$$

Kc: Crop coefficient.
Kcb: Basal crop coefficient.
Ke: Soil evaporation coefficient.
ETa: Actual evapotranspiration (mm per day).
ETo: Reference evapotranspiration (mm per day).

The Kc values during the growing seasons were considered equal to the Kcb values, since the dates chosen to develop the Kcb-VI relationship were always four days or more after an irrigation or rain events allowing time for the soil surface to dry. Thus, the effect of soil surface evaporation (Ke) on the Kcb values is insignificant, especially when using subsurface drip irrigation when Ke is near to zero, while transpiration potentially occurs without any limitation, for more details see Campos et al. (2017). In fact, soil evaporation can hardly fall to zero, even for dry ecosystems Perez-Priego et al. (2018). ETo values were collected at the automated weather station near the study site. Thus, the Kcb-VI relationship for sugarcane was developed and incorporated in SETMI. SETMI applies a regression-based model relating accumulated growing degree-day (base temperature equal to 18 °C) to the daily SAVI for obtaining a daily Kcb, on days when remote sensing inputs are not available (Campos et al., 2017), following the Eq. 6, also, used for irrigation management by Barker et al. (2018).

$$SAVI_i = \min[(exp^{(a1(CGDDi)+b1)}, \quad SAVI_x exp^{(-exp^{(a2(CGDDi)+b2)})}] \quad (6)$$

$SAVI_i$: estimated SAVI for the current day.
$SAVI_x$: maximum SAVI, taken here to be the peak computed value for a given pixel.
$CGDD_i$: cumulative growing degree days for the current day.
a and *b*: linear regression coefficients, with the subscripts 1 and 2 representing the stages of growth, increasing SAVI and decreasing SAVI, respectively.

SAVI values for bare soil were set at 0.12 after harvesting beginning the new growing season, and 0.45 at the end of the crop maturation for a final Kcb equal to 0.7, as described in Allen et al. (1998). The occurrence of a Kcb value greater than 0 for bare soil conditions has been demonstrated repeatedly in the literature and Wright (1982) proposed the use of a residual Kcb equal to 0.15, even in the absence of vegetation, also

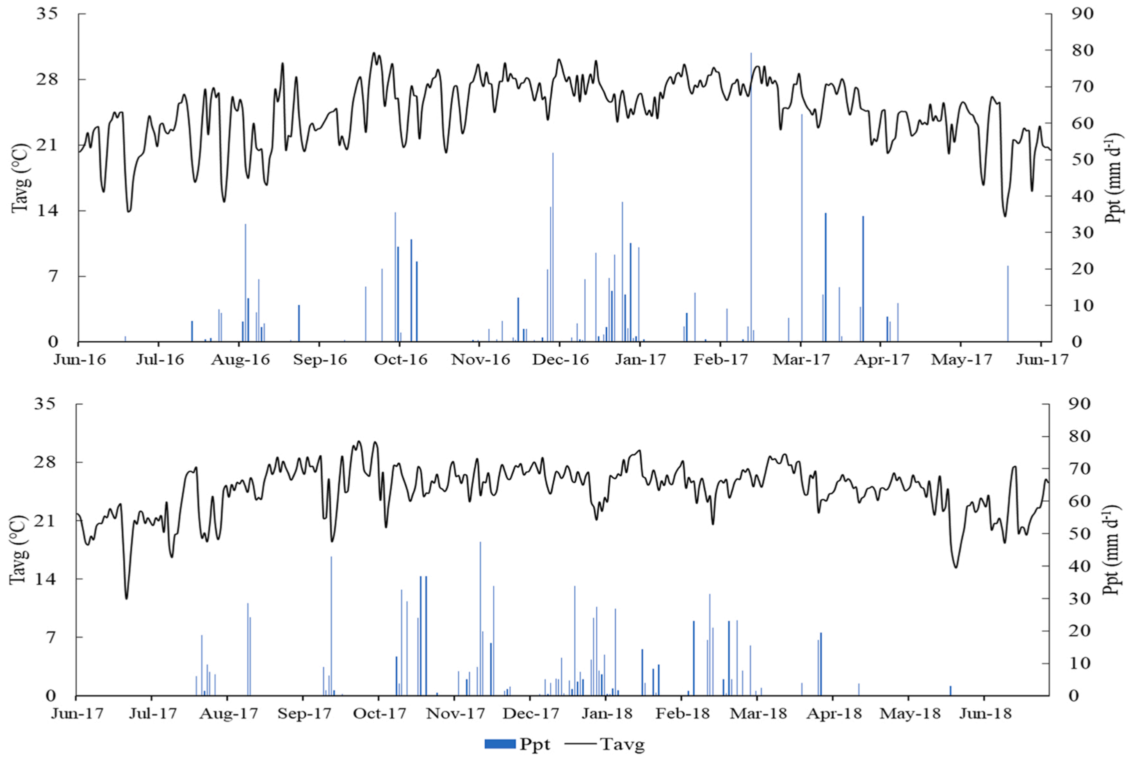

Fig. 3. Daily gross precipitation (Ppt) and daily average temperature (Tavg) over the growing seasons 2016–2017 (4th ratoon) and 2017–2018 (5th ratoon).

found in the FAO 56 (Allen et al., 1998) and most of the empirical relationships published between Kcb and VI (Bausch and Neale, 1987; Campos et al., 2010; Hunsaker et al., 2003; Neale et al., 1989). As empirically demonstrated by Torres and Calera (2010), this residual evaporation can be expected for bare soil for more than 30 days after the irrigation events or precipitation, even in the total absence of plants transpiring in the field.

Additionally, after estimating ETa, crop water productivity (WP_{p+i}), crop water productivity of irrigation (WP_i) and crop water productivity based on evapotranspiration (WP_{ET}) were calculated following Eqs. 7, 8, and 9.

$$WP_{P+i} = \frac{Yield}{p+i} \tag{7}$$

$$WP_i = \frac{Yield}{i} \tag{8}$$

$$WP_{ET} = \frac{Yield}{ET} \tag{9}$$

WP_{p+i} = Crop water productivity (Kg m^{-3}).
WPi = Crop water productivity of irrigation (Kg m^{-3}).
WP_{ET} = Crop water productivity based on evapotranspiration (Kg m^{-3}).
p = Precipitation (mm).
i = Irrigation (mm).
ETa = Actual evapotranspiration (mm).

The calculations were done using observed field irrigation data, yield data, and modeled evapotranspiration to estimate WP_{p+i}, WP_i, and WP_{ET}.

2.4. Statistical analysis

The energy balance components and the ETa estimated by the SETMI model were compared with the data measured in the field through the EC flux tower. To measure the accuracy of the model, RMSE (root mean squared error) and Bias indicators were applied according to Eqs. 10 and 11 respectively.

$$RMSE = \sqrt{\sum\nolimits_{i=1}^{n} \frac{(Y_i - \bar{Y}_i)^2}{n}} \tag{10}$$

RMSE: root mean squared error.
n: sample size.
Y: observed variable.
Ȳ: modeled variable

$$Bias = \sum\nolimits_{i=0}^{n} \frac{(Y_i - \bar{Y}_i)}{n} \tag{11}$$

n: sample size.
Y: observed variable.
Ȳ: modeled variable.

The Kcb-VI relationship was evaluated by applying the statistical indicators R-square that indicate the approximation of estimated values in relation to observed values. Additionally, Pearson's simple correlation coefficient "ρ" was used to analyze the correlation strength between SAVI and Kcb (Eq. 12).

$$\rho = \frac{\sum_{i=1}^{n} (x_i - \dot{x})(y_i - \dot{y})}{(n-1) S_x S_y} \tag{12}$$

ρ: simple Pearson correlation.
ẋ: observed mean ETa (mm d^{-1}).
S_x: observed standard deviation ETa (mm d^{-1}).
ẏ: modeled mean ETa (mm d^{-1}).
S_y: modeled standard deviation ETa (mm d^{-1}).
n: sample size.

3. Results and discussion

Fig. 3 presents the daily precipitation and average daily temperature over the growing seasons 2016–2018 (fourth ratoon) and 2017–2018

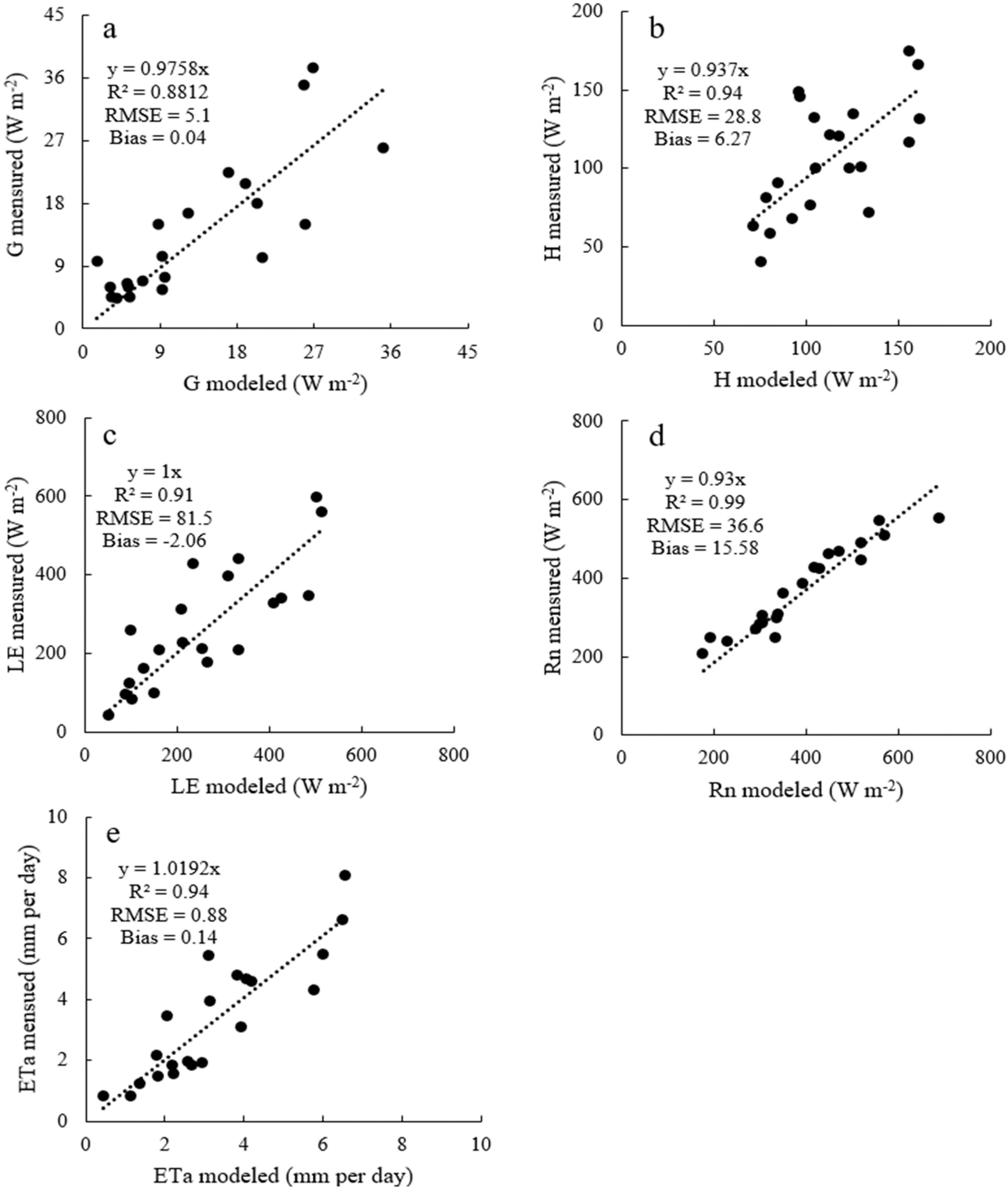

Fig. 4. Measured energy balance components (G: soil heat flux - a; H: sensible heat flux - b; LE: latent heat flux – c; Rn: net radiation - d) and actual evapotranspiration (ETa - e) by the Eddy Covariance method compared with the values modeled by the SETMI for sugarcane in the period 2016–2018.

(fifth ratoon) recorded for the flux tower set up in the field.

Overall, the fourth and fifth growing seasons presented the same average temperature equal to 24.6 °C, greater than the historical average for the region (23.3 °C). Accumulated precipitation was 988 mm and 974 mm in the fourth and fifth ratoon years respectively, lower than the average historical amount of 1242 mm. Precipitation for both ratoons was very irregular over the growing seasons, resulting in only 46 days and 53 days with precipitation over 5 mm respectively, distributed from October to February (rainy season). Sugarcane in Brazil is purposefully planted in June and July to be harvested after one year during the dry season to increase the Brix percentage in the stalk resulting in higher sugar content and ethanol production. Irrigation is required mainly after planting, even though precipitation is higher from October to February, it is common for dry spells to occur during the

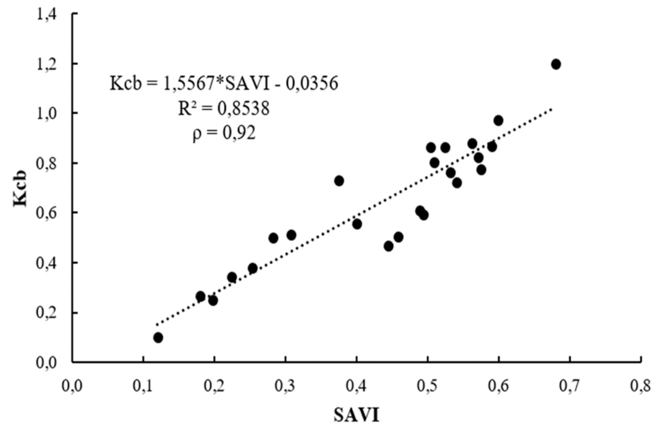

Fig. 5. Correlation between the basal crop coefficient (Kcb) and Soil Adjusted Vegetation Index (SAVI) for sugarcane crop.

rainy season, so based on this analysis, irrigation is essential to maintain proper soil water content in the root zone for reaching high yields.

Using data from the two growing seasons, the EB components and ETa ratio estimated from the SETMI model based on TSEB and the ETa estimated by the EC system is shown in Fig. 4. According to Mukaka (2012), the EB components values indicated acceptable performance mainly for Rn and LE with R^2 over 0.90 and bias equal to 15.58 and − 2.06 respectively. For G and H, R^2 values also were above 0.80 and RMSE showed low values with bias close to zero. Commonly, G values have little influence on EB because their values are considered very low, less than 5% of Rn in this study. So, as shown in Fig. 4, the modeled results are consistent with ground flux measurements, as a result, ETa presented a high correlation between the values of the EC and modeled by the TSEB, overestimating the ETa values by less than 2% with R^2 of 0.94 and bias equal to 0.14. Similar results also were observed by Yang et al. (2018) and Campos et al. (2017).

The SETMI hybrid model requires a specific Kcbrf based on simple linear correlation using Kcb values obtained from field measurements combined with SAVI values from remote sensing, so it was built for sugarcane under tropical conditions. The Kcb-SAVI relationship obtained is shown in Fig. 5.

The resulting linear equation shown in Fig. 5 indicates a robust correlation between the SAVI and the data measured in the field, with an R^2 value of 0.85 and a "ρ" of 0.92. This approach has already been used for other crops such as corn and soybean in the United States (Campos et al., 2017), vineyards in Spain (Campos et al., 2010), and wheat in Morocco (Duchemin et al., 2006). Daily SAVI values were estimated using GDD to obtain their values over growing seasons shown in Fig. 6.

The maximum SAVI value observed was 0.60 and 0.59 for the 4th and 5th ratoons respectively. After this point, because of the maturation stage, the SAVI values decrease until harvesting due to reduction in green leaf area index which is expected in this stage as shown in Gonçalves et al. (2017) and Silva et al. (2012). After harvest, the SAVI values decrease to close to bare soil values around 0.12. Using SAVI-GDD to record daily SAVI represented crop development very well for the entire growing seasons. Following daily SAVI values over seasons and following the Kcb-SAVI relationship implemented based on Fig. 5, the SETMI model was able to accurately estimate the Kcb over growing seasons as shown in Fig. 7.

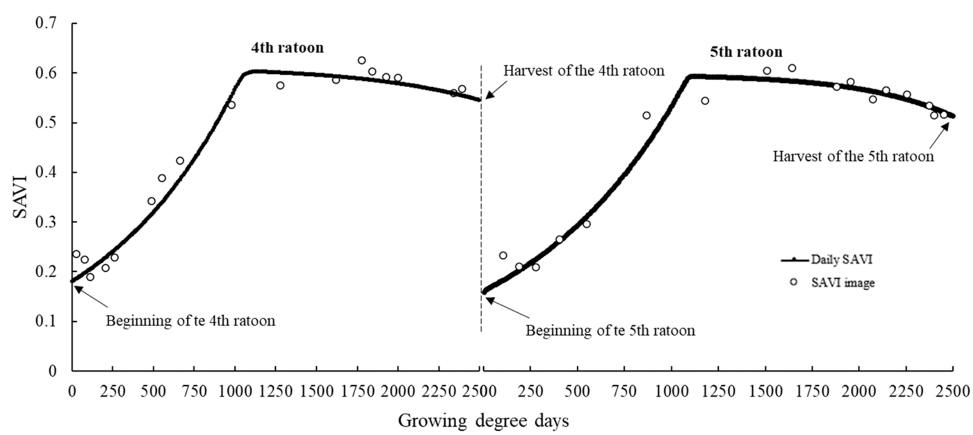

Fig. 6. Temporal evolution of the SAVI values derived from Landsat 8 images for sugarcane for the 4th and 5th growing season irrigated by subsurface drip irrigation.

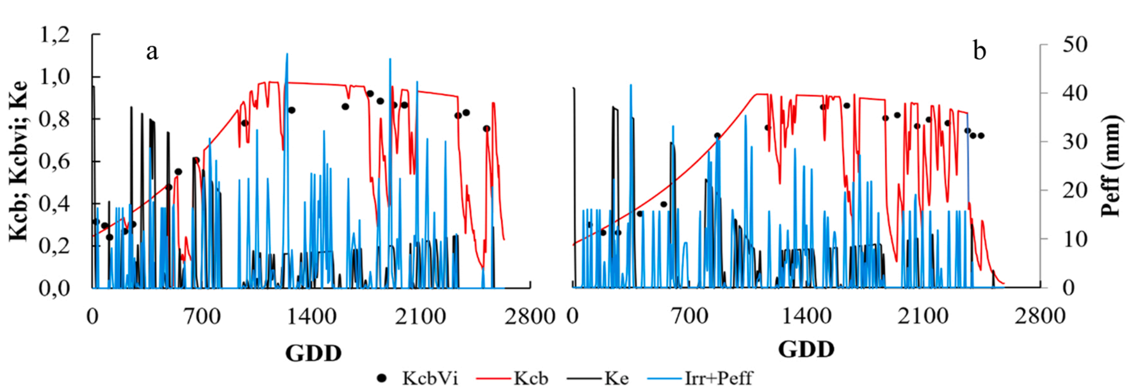

Fig. 7. Estimated basal crop coefficient (kcb), reflectance basal crop coefficient (Kcbvi), evaporation coefficient (Ke) and effective precipitation over growing season for 4th ratoon (a) and 5th ratoon (b) based on growing degree days (GDD).

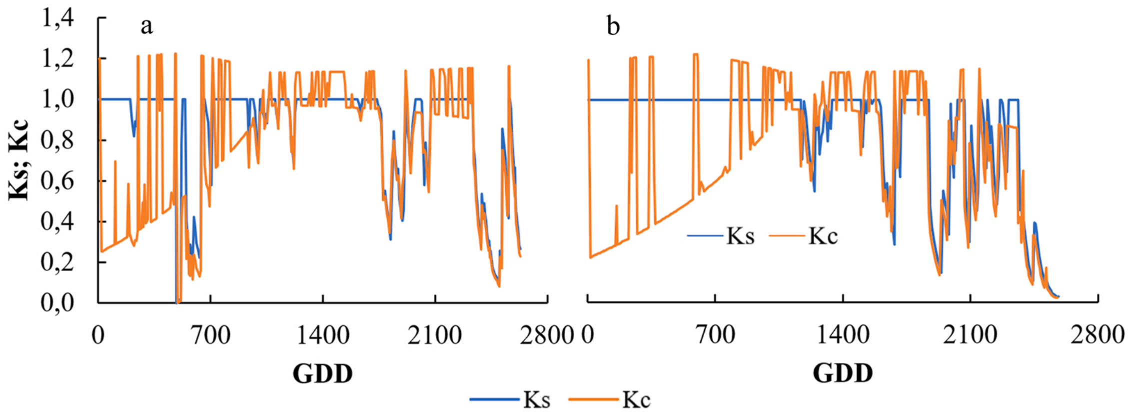

Fig. 8. Crop stress coefficient (Ks) and crop coefficient (Kc) over the 4th and 5th seasons based on degree-days of growth (GDD).

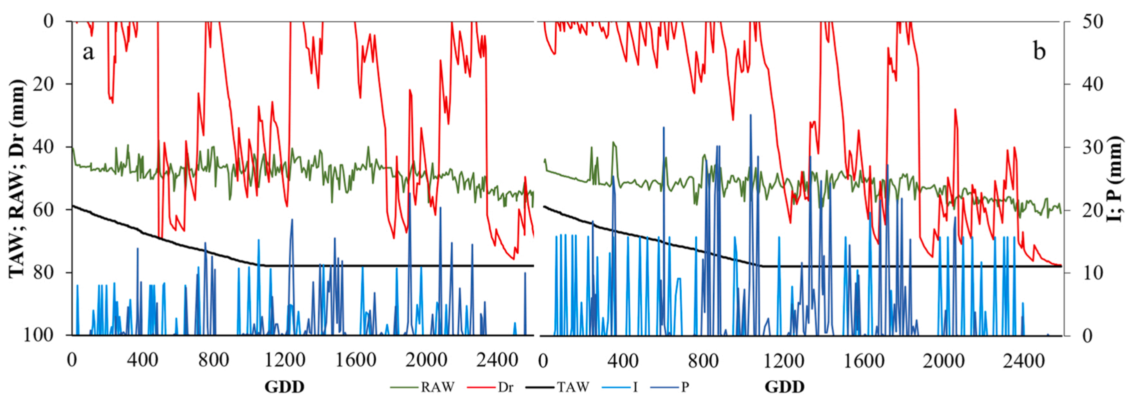

Fig. 9. Total water available (TAW), Readily available water (RAW), depletion (Dr), irrigation (I) and effective precipitation (Peff) over the 4th (a) and 5th (b) growing seasons based on growing degree days (GDD).

The initial Kcb was about 0.15 increasing until reach the maximum value of 0.97 for the 4th ratoon and 0.95 for 5th on average. Results regarding the entire season Kcb averaged were equal to 0.62 and 0.58 for the 4th and 5th ratoons, respectively (Fig. 7). Conversely, the Ke values for both seasons were high at the beginning of the seasons and decreased with the crop development due to the higher leaf area index. Because the drip tapes of the irrigation system are buried at 0.40 m and the region shows high precipitation rates, likely all the evaporation water was from precipitation. Before reaching full cover during the development stage, there were many rainy days with more than 10 mm in both ratoons. These Kcb and Ke values for sugarcane are similar to Allen et al. (1998) and Silva et al. (2012). The Kc low spikes in Fig. 8 are due to soil water depletion in the root zone of the sugarcane leading to a crop stress (Ks) coefficient value below 1 represented in Fig. 8 caused by the soil water depletion (Dr) above the readily water available (RAW), causing water stress in plants (Fig. 9).

A severe drought occurred during the development stage of the crop and the irrigation system was not able to apply the required water demand which resulted in water stress in the plants for the 4th growing season. Both seasons showed some level of water stress after the crop reached the peak Kc (full cover stage) when the irrigation depth required was very high due to the lack of precipitation combined with high evapotranspiration rates during the period, being this region (northwest of the state of São Paulo) known as the region with the highest

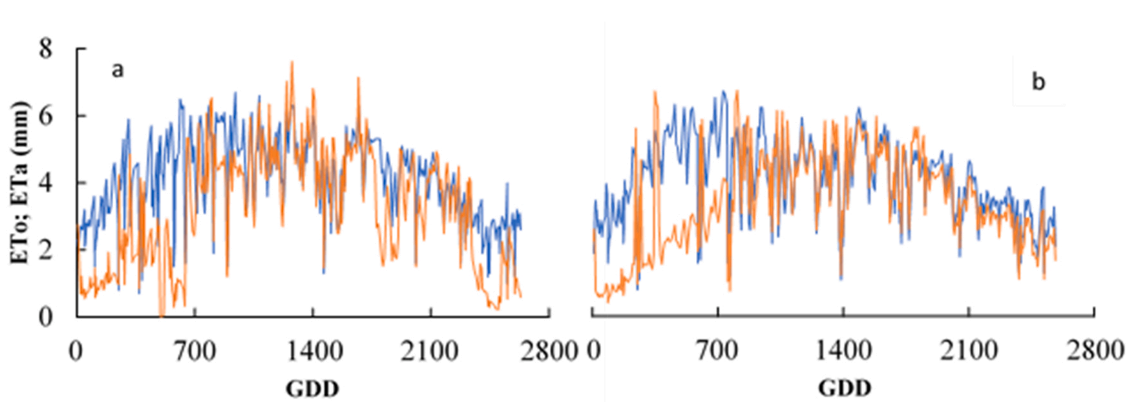

Fig. 10. Daily reference evapotranspiration (ETo, mm per day)) and actual evapotranspiration (ETa, mm per day) from meteorological weather station and modeled adjusted evapotranspiration over growing seasons 4th ratoon (a) and 5th ratoon (b).

Table 2
Accumulated actual crop evapotranspiration (ETac), reference evapotranspiration (ETo), total precipitation (Pt), total applied irrigation (It), yield, crop water productivity of total (WP_{p+i}), crop water productivity of irrigation (WP_i and crop water productivity based on evapotranspiration (WP_{ET}) for the period 2016–2017 and 2017–2018.

Ratoon	ETac (mm)	ETo (mm)	P_t (mm)	I_t (mm)	Yield (t ha^{-1})	WP_{p+i} (Kg m^{-3})	WP_i (Kg m^{-3})	WP_{ET} (Kg m^{-3})
2016–2017	1048	1406	988	584	127	12,8	21,7	12.1
2017–2018	1003	1408	974	560	121	12,4	21,6	12.4
Average	1025	1407	981	572	124	12,6	21,7	12,3

evapotranspiration rate in the state (Hernandez et al., 2003). The water stress was observed mainly during the final stages of growth when the irrigation events are reduced to guarantee the accumulation of sugar in the stalks. For irrigation purposes, however, the period of greatest susceptibility to water deficits is the stage of rapid crop development, when the plants already have a high leaf area index and need a greater amount of water for gas exchange with the atmosphere (Pires et al., 2008; Da Silva and Costa, 2004).

Overall, the average Kc throughout the period was 0.73 and 0.70 for the 4th and 5th ratoons respectively, and maximum Kc of about 1.23 for both growing seasons, similar to Kc values to Allen et al. (1998) and Doorenbos and Kassam (1979), (Fig. 8).

In Fig. 9, it is noted that the increase of the total available water (TAW) over the growing seasons following the root zone growth until reach the maximum value equal of about 78 mm around 1000 GDD. It also is observed that at the end of the season (about 30 days before harvesting - irrigation cut off), the Dr value was close to TAW corresponding to the period with maximum accumulated sugar in the stalks, which is required for sugarcane production. The TAW increases as the root system increase over time, however, when harvesting occurs, the sugarcane loses the ability to produce elaborate sap (photosynthesis is interrupted), in this way, it also loses the ability to nourish the root system, so part of the roots dies and, TAW decreases after harvest and increases again over time with roots system recovering. The negative Dr values are due to heavy rains (over 25 mm) causing percolation.

The ETa values estimated by the SETMI hybrid model followed the same tendency of ETo values, corroborating with Allen et al. (1998), who describes that ETa values are directly influenced by the ETo values (Fig. 10). The total ETa was 1054 mm and 1168 mm respectively for the 4th and 5th growing seasons, on average ETo and ETa presented values of 3.8 mm per day and 2.9 mm per day for the 4th season and, 3.9 mm per day and 3.2 mm per day for the 5th respectively.

The greater discrepancy between ETa and ETo was observed at the beginning of the seasons when the plants are still young presenting low Kc values. After 700 GDD, with greater leaf area index development and consequently greater Kc values, the ETo and ETa were closer over both growing seasons. Accumulated actual evapotranspiration (ETac) and field data were used to estimate $WP_{p+i,}$ WP_i, and WP_{ET}, as shown in Table 2.

Overall, all the WP values were very similar between the growing seasons because of the yield, irrigation, precipitation, and ETo were very close between ratoons, except WP_{ET} when the 4th ratoon was about 16% greater than the 5th ratoon mainly because the lower values of ETa. These results were slightly lower than Leal et al. (2017) in southeastern Brazil and greater than Silva et al. (2011) in northeastern Brazil. According to Teixeira et al. (2011), WP in a study in the state of São Paulo ranged from 2.8 to 6.0 kg m^{-3}, much lower than our findings in this research, likely due to the fact that in most of Brazil, the sugarcane is not irrigated. Regarding the yield, both ratoons showed values greater than the Brazilian average (69 t ha^{-1}) (CONAB, 2021).

4. Conclusions

This research was carried out in the largest sugarcane producing region of Brazil using the SETMI hybrid model to estimate evapotranspiration and rootzone water balance of a growing sugarcane field, over two growing seasons. The modeled EB components using the SETMI hybrid model agreed well with the eddy covariance system values. The Kcb-SAVI relationship for sugarcane presented a strong correlation with an R^2 value of 0.85 and an "ρ" of 0.92. As result, the SETMI hybrid model can be applied to the soil water balance for monitoring the irrigation water management for sugarcane under Brazilian soil and climate conditions. The hybrid model produced suitable daily estimated Kcb values for the two growing seasons through the Kcb-SAVI relationship, with suitable remote-sensing-based soil water balance, monitoring the development of the crop, and estimating the ETa during the evaluated growing periods.

SETMI model is an attempt to take advantage of the ability of Kcbrf methods to compute daily ETa on dates without remote sensing inputs and, taking advantage of the TSEB, which is not affected by the modeled water balance. The hybrid model using the Kcb-SAVI relationship for irrigated sugarcane could be tested under rainfed condition and different ratoons cycles for future researches.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Acknowledgements

The authors thank to the UNESP Irrigation and Drainage Program and the Daugherty Water for Food Global Institute of the University of Nebraska for the scientific technical support and partial funding. Thanks also to CAPES (Process 88881.189165/2018-01), CNPq (Process 404.229/2013-1), and FAPESP (Process 2.009/52.467-4; 2020/08365-1) for the financial support. We are grateful to the engineers Francisco Evandro Albino, Leandro Melo and Marcelo Agudo Romão for the field works support.

References

Allen, R.G., Wright, J.L., 1997. Translating wind measurements from weather stations to agricultural crops. J. Hydrol. Eng. 1, 26–35.
Allen, R.G., Pereira, L.S., Raes, D., Smith, M., 1998. Crop evapotranspiration - Guidelines for computing crop water requirements. Roma: FAO Irrigation and Drainage, Paper 56, Italy, p. 297.
ANA – Agência Nacional das Águas., 2020. Atlas da irrigação. Brasilia, http://atlasirrigacao.ana.gov.br/.
Anderson, M.C., Norman, J.M., Diak, G.R., Kustas, W.P., Mecikalski, J.R., 1997. A two-source time-integrated model for estimating surface fluxes using thermal infrared remote sensing. Remote Sens. Environ. 60, 195–216.
Bai, Y., Bhattarai, N., Mallick, K., Zhang, S., Hu, T., Zhang, J., 2022. Thermally derived evapotranspiration from the surface temperature initiated Closure (STIC) model improves cropland GPP estimates under dry conditions. Remote Sens. Environ. 271, 112901.
Barker, J.B. 2017. Spatial irrigation management using remote sensing water balance modeling and soil water content monitoring, doctoral thesis, p. 319, University of Nebraska, Lincoln.
Barker, J.B., Neale, C.M.U., Heeren, D.M., Suyker, A.E., 2018. Evaluation of a hybrid reflectance-Based crop coefficient and energy balance evapotranspiration model for irrigation management. ASABE 61 (2), 533–548.
Bastiaanssen, W.G.M., Pelgrum, H., Wang, J., Ma, Y., Moreno, J.F., Roenrink, G.J., Van Der Wal, T. 1998. A remote sensing surface energy balance algorithm for land (SEBAL) 2. Validation. Journal of Hydrology, v. 212–213, p. 213–229.

Bausch, W.C., Neale, C.M.U., 1987. Crop coefficients derived from reflected canopy radiation - a concept. Trans. ASAE 3, 703–709.

Bispo, R.C., 2020. Measurements and modeling of evapotranspiration in sugarcane in northwest São Paulo. Doctoral thesis, p.94, State University of São Paulo, Botucatu.

Campos, I., Neale, C.M.U., Calera, A., Balbontin, C., González-Piqueras, J., 2010. Assessing satellite-based basal crop coefficients for irrigated grapes (Vitis vinifera L.). Agric. Water Manag., Amst. 98, 45–54.

Campos, I., Balbontín, C., González-Piqueras, J., González-Dugo, M.P., Neale, C.M.U., Calera, A., 2016. Combining a water balance model with evapotranspiration measurements to estimate total available soil water in irrigated and rainfed vineyards. Agric. Water Manag. Amst. V. 165, 141–152.

Campos, I., Neale, C.M.U., Suyker, A., Arkebauer, T.J., Gonçalves, I.Z., 2017. Reflectance based crop coefficients REDUX: for operational evapotranspiration estimates in the age of high producing hybrid varieties. Agric. Water Manag., Amst. 187, 140–153.

Campos, I., Neale, C.M.U., Arkebauer, T.J., Suyker, A.E., Gonçalves, I.Z., 2018. Water productivity and crop yield: a simplified remote sensing driven operational approach. Agric. For. Meteorol. Amst. 249, 501–511.

CONAB, Companhia Nacional de Abastecimento, 2021. Acompanhamento da safra brasileira: Cana-de-açúcar, v.8 - Safra 2021/2022. Terc. Levant., Brasília 1–63.

Da Silva, A.L.C., Costa, W.A.J.M. de, 2004. Varietal variation in growth, physiology and yield of sugarcane under two contrasting water regimes. Trop. Agric. Res., V. 16, 1–12.

Dias, H.B., Sentelhas, P.C., 2019. Dimensioning the impact of irrigation on sugarcane yield in Brazil. Sugar Tech. 21, 29–37. https://doi.org/10.1007/s12355-018-0619-x.

Doorenbos, J., Kassam, A.H., 1979. Efectos del agua sobre el rendimiento de los cultivos. Roma, F. A. O., 212p. (FAO. Estudio Riego y Drenage, 33).

Duchemin, B., Hadria, R., Er-raki, S., Boulet, G., Maisongrande, P., Chehbouni, A., Escadafal, R., Ezzahar, J., Hoedjes, J.C.B., Kharrou, M.H., Khabba, S., Mougenot, B., Olioso, A., Rodriguez, J.C., Simmoneaux, V., 2006. Monitoring wheat phenology and irrigation in central Morocco: on the use of relationships between evapotranspiration, crop coefficients, leaf area index and remotely-sensed vegetation indices. Agric. Water Manag., V. 79, 1–27.

Foster, T., Gonçalves, I.Z., Campos, I., Neale, C.M.U., Brozović, N., 2019. Assessing landscape scale heterogeneity in irrigation water use with remote sensing and in situ monitoring. Environ. Res. Lett.. 2, 40.

Geli, H.M.E., Neale, C.M.U., 2012. Spatial evapotranspiration modelling interface (SETMI). In remote sensing and hydrology, editado por Neale, C.M.U.; Cosh, M.H. Sciences. Int Assoc Hydrological, Wallingford, pp. 171–174.

Gonçalves, I.Z., Barbosa, E.A.A., Santos, L.N.S., Nazario, A.A., Feitosa, D.R.C., Tuta, N.F., Matsura, E.E., 2019. Nutritional balance and production of sugarcane irrigated with treated wastewater through subsurface drip. Irrig. Sci. Berl. 37, 207–217.

Gonçalves, I.Z., Mekonnen, M.M., Neale, C.M.U., Campos, I., Neale, M.R., 2020. Temporal and spatial variations of irrigation water use for commercial corn fields in Central Nebraska. Agric. Water Manag., Amst. 228, 105.

Gonçalves, IZ.; Barbosa, EAA.; Santos, LNS.; Nazário, AA.; Feitosa, DRC., Tuta, NF., Matsura, EE., 2017. Water relations and productivity of sugarcane irrigated with domestic wastewater by subsurface drip, Agricultural Water Management, Elsevier, vol. 185(C), pages 105–115.

González-Dugo, M.P., Escuin, S., Cano, F., Cifuentes, V., Padilla, F.L.M., Tirado, J.L., Oyonarte, N., Fernández, P., Mateos, L., 2013. Monitoring evapotranspiration o irrigated crops using crop coefficients derived from time series of satellite images II. Application on basin scale. Agric. Water Manag., Amst. 125, 92–104.

Ham, J.M., 2005. Useful equations and tables in micrometeorology. In: Hatfield, J.L., Baker, J.M. (Eds.), Micrometeorology in Agricultural Systems. American Society of Agronomy, Crop Science Society of America, and Soil Science Society of America, Madison, WI, pp. 533–560.

Hernandez, F.B.T., Souza, S.A.V., Zocoler, J.L., Frizzone, J.A., 2003. Simulação e efeito de veranicos em culturas desenvolvidas na região de Palmeira d'Oeste, Estado de São Paulo. Eng. Agríc., Jaboticabal 1, 21–30.

Huete, A.R., 1988. A soil-adjusted vegetation index (SAVI). Remote Sens. Environ. 3, 295–309.

Hunsaker, D.J., Pinter, P.J., Barnes, E.M., Kimball, B.A., 2003. Estimating cotton evapotranspiration crop coefficients with a multispectral vegetation index. Irrig. Sci., Berl., V. 22, 95–104.

Jayanthi, H., Neale, C.M.U., Wright, J.L., 2007. Development and validation of canopy reflectance-based crop coefficient for potato. Agric. Water Manag. 88 (1–3), 235–246.

Leal, D.P.V., Coelho, R.D., Barbosa, FS., Júnior Fraga, EF., Mauri, R., Santos, L.C., 2017. Water productivity for sugar and biomass of sugarcane varieties. Revista Brasileira Engenharia Agrícola Ambental, v. 2, n. 9. https://doi.org/10.1590/1807–1929/agriambi.v21n9p618–622.

LICOR , Eddypro software instruction manual V 2020a 7.⟨https://www.licor.com/documents/1ium2zmwm6hl36yz9bu4⟩.

LICOR Tovi user guide V 2 2020b 8.⟨https://licor.app.boxenterprise.net/s/7t9z11sw53qg1qe4dhga84mwgvs3e8ni⟩.

Mecikalski, J.M., Diak, G.R., Anderson, M.C., Norman, J.M., 1999. Estimating fluxes on continental scales using remotely sensed data in an atmosphere-land exchange model. J. Appl. Meteorol., V. 38, 1352–1369.

Mukaka, M.M., 2012. Statistics corner: a guide to appropriate use of correlation coefficient in medical research. Malawi Med. J. J. Med. Assoc. Malawi 24 (3), 69–71.

Neale, C.M.U., Bausch, W.C., Heerman, D.F., 1989. Development of reflectance-based crop coefficients for corn. Trans. ASAE, V. 32, 1891–1899.

Neale, C.M.U., Geli, H.M.E., Kustas, W.P., Alfieri, J.G., Gowda, P.H., Evett, S.R., Prueger, J.H., Hipps, L.E., Dulaney, W.P., Chavez, J.L., French, A.N., Howell, T.A., 2012. Soil water content estimation using a remote sensing based hybrid evapotranspiration modeling approach. Adv. Water Resour., V. 50, 152–161.

Neale, C.M.U., Gonzalez-Dugo, M.P., Serrano-Perez, A., Campos, I., Mateos, L., 2021. Cotton canopy reflectance under variable solar zenith angles: Implications of use in evapotranspiration models. Hydrological processes, v- 35 Issue: 6. DOI: 10.1002/hyp.14162. Published: JUN 2021.

Norman, J.M., Kustas, W.P., Humes, K.S., 1995. A two-source approach for estimating soil and vegetation energy fluxes in observations of directional radiometric surface-temperature. Agric. For. Meteorol. Amst. 3–4, 263–293.

Norman, J.M., Anderson, M.C., Kustas, W.P., French, A.N., Mecikalski, J., Torn, R., Diak, G.R., Schmugge, T.J., Tanner, B.C.W., 2003. Remote sensing of surface energy fluxes at 101-m pixel resolutions. Water Resour. Res. 39, 1221.

Peel, M.C., Finlayson, B.L., Mcmahon, T.A., 2007. Updated world map of the Köppen-Geiger climate classification. Hydrol. Earth Syst. Sci. 11, 1633–1644. https://doi.org/10.5194/hess-11-1633-2007.

Perez-Priego, O., Katul, G., Reichstein, M., El-Madany, T.S., Ahrens, B., Carrara, A., Scanlon, T.M., Migliavacca, M., 2018. Partitioning eddy covariance water flux components using physiological and micrometeorological approaches. J. Geophys. Res.: Biogeosciences 123, 3353–3370.

Pires, R.C.M., Arruda, FB., Sakai, E., 2008. Irrigação e drenagem. In: DINARDO-MIRANDA, L. L., VASCONCELOS, A. C. M., LANDELL, M. G. A. (Ed.). Cana-de-açúcar. Campinas: Instituto Agronômico, 882p.

Santos, H.G., Jacomine, P.K.T., Anjos, L.H.C., Oliveira, V.A., Lumbreras, J.F., Coelho, M. R., Almeida, J.A., Araújo Filho, A., J.C., Oliveira, J.B., Cunha, T.J.F, 2018. Brazilian agricultural research corporation. Brazilian soil classification system, 5 ed. Embrapa Soils, Brasília, p. 564.

Silva, T.G.F., Moura, M.S.B., Zolnier, S., Soares, J.M., Vieira, V.J.S., Gomes Júnior, W.F., 2011. Demanda hídrica e eficiência do uso de água da cana-de-açúcar irrigada no semiárido brasileiro. Rev. Bras. De. Eng. Agríc. e Ambient., V. 15, 1257–1265. https://doi.org/10.1590/S1415-43662011001200007.

Silva, V., Borges, C., Farias, C., Singh, V., Albuquerque, W., Silva, B., 2012. Water requirements and single and dual crop coefficients of sugarcane grown in a tropical region, Brazil. Agric. Sci. 3, 274–286. https://doi.org/10.4236/as.2012.32032.

Teixeira, A.H.C., Leivas, J.F., Ronquim, C.C., Victoria, D.C., 2011. Sugarcane water productivity assessments in the São Paulo state, Brazil. Int. J. Remote Sens. Appl. (IJRSA) V. 6, 2016. https://doi.org/10.14355/ijrsa.2016.06.009.

Torres, E.A., Calera, A., 2010. Bare soil evaporation under high evaporation demand: a proposed modification to the FAO-56 model. Hydrol. Sci. J., V. 55, 303–315.

Twine, T.E., Kustas, W.P., Norman, J.M., Cook, D.R., Houser, P.R., Meyers, T.P., Prueger, J.H., Starks, P.J., Wesely, M.L., 2000. Correcting eddy-covariance flux underestimates over a grassland. Agric. For. Meteorol., Amst. 103, 279–300.

UNESP Universidade Estadual Paulista. Acesso à base diária: Canal CLIMA. Ilha Solteira: UNESP - Faculdade de Engenharia - Departamento de Fitossanidade e Engenharia Rural e Solos - Área de Hidráulica e Irrigação, 2019. Disponível em: Acesso em 10 de julho de 2019.

Uribe, R.A.M., Gava, G.J.C., Saad, J.C.C., Kolln, O.T., 2013. Ratoon sugarcane yield integrated drip-irrigation and nitrogen fertilization. Engenharia Agrícola 33(6): 1124–1133, 2013. 10.1590/S0100–69162013000600005.

USDA-NRCS., 2004. Estimation of Direct Runoff from Storm Rainfall Part 630 Hydrology, National Engineering Handbook. Washington, D. C.: U. S. Department of Agriculture, Natural Resources Conservation Service.

Venancio, P.L., Mantovani, C.E., Amaral, C.H., Neale, C.M.U., Gonçalves, I.Z., Filgueiras, R., Campos, I., 2019. Forecasting corn yield at the farm level in Brazil based on the FAO-66 approach and soil-adjusted vegetation index (SAVI). Agric. Water Manag., Amst., V. 225, 303–315.

Wright, J.L., 1982. New evapotranspiration crop coefficients. J. Irrig. Drain. 108, 57–74.

Yang, Y., Anderson, M.C., Gao, F., Wardlow, B., Hain, C.R., Otkin, A.J., Alfieri, J., Yang, Y., Sun, L., Dulaney, W., 2018. Field-scale mapping of evaporative stress indicators of crop yield: an application over Mead, NE, USA. Remote Sens. Environ. 210, 387–402.

Chávez, J.L., Neale, C.M.U., Prueger, J.H., Kustas, W.P., 2008. Daily evapotranspiration estimates from extrapolating instantaneous airborne remote sensing ET values. Irrigation Science 27, 67–81.

Field, R.T., Heiser, M., Strebel, D.E., 1994. Measurements of surface fluxes. The FIFE Information System, Summary Document. The FIFE Information System, Summary Document.

Weaver, H.L., 1990. Temperature and humidity flux-variance relations determined by one-dimensional eddy correlation. Boundary-Layer Meteorol 53, 77–91. https://doi.org/10.1007/BF00122464.