Available online at http://www.journalcra.com

International Journal of Current Research
Vol. 9, Issue, 04, pp.48601-48610, April, 2017

INTERNATIONAL JOURNAL
OF CURRENT RESEARCH

ISSN: 0975-833X

RESEARCH ARTICLE

ASSESSING SUGARCANE EVAPOTRANSPIRATION BASED ON A BIOPHYSICAL APPROACH

*,[1]Kassio S. Carvalho, [1]Murilo S. Vianna, [2]Daniel S. P. Nassif, [1]Leandro G. Costa, [1]Marcos V. Folegatti and [1]Fábio R. Marin

[1]University of São Paulo (USP), College of Agriculture "Luiz de Queiroz" (ESALQ), Piracicaba-SP, Brazil
[2]Federal University of São Carlos, Campus Lagoa do Sino, Buri-SP, Brazil

ARTICLE INFO

Article History:
Received 17th January, 2017
Received in revised form
25th February, 2017
Accepted 22nd March, 2017
Published online 20th April, 2017

Key words:

Saccharum officinarum L.,
Penman-Monteith,
Transpiration,
Soil evaporation.

ABSTRACT

Brazil is the largest producer of sugarcane in the world; due to the increased use of irrigation systems in sugarcane fields, it is important to search for methods to assist with the rational use of irrigation water. Among the methods used to quantify transpiration, the Penman-Monteith (PM) method is based on a strong biophysical approach. The study aimed to use the PM method as a basis for estimating the crop transpiration of sugarcane. The experiment was conducted in an experimental area of 2.5 ha, irrigated by center pivot. To use the PM model, it was necessary to use sub-models for estimating the crop aerodynamic resistance (ra), the canopy energy balance (Rnef), vapor pressure deficit in the crop environment (Δe), and canopy resistance (rc). When relating Rg with Rnef and net radiation from above the cane field, there is an R^2 of 0.85 and 0.84, respectively. Ra was strongly influenced by the wind speed and the proposed rc sub-model performed well, with an R^2 of 0.62. To quantifying the temperature of the canopy can determine Δe variable of PM model and the sub-model used to estimate the temperature of the canopy presented an R^2 of 0.84. PM model was relating with transpiration measured by sap flow sensors and presented a R^2 of 0.72 and relating the evapotranspiration measured with the method of the Bowen ratio (BRM) with the ETc model proposed, there is an R^2 of 0.54, and an angular coefficient of 1.09.

Citation: Kassio S. Carvalho, Murilo S. Vianna, Daniel S. P. Nassif, Leandro G. Costa, Marcos V. Folegatti and Fábio R. Marin, 2017. "Assessing sugarcane evapotranspiration based on a biophysical approach", *International Journal of Current Research*, 9, (04), 48601-48610.

INTRODUCTION

Introduced in Brazil by the Portuguese in the colonial period, sugarcane has become one of the main sources of financial resources; the large amount of sugar in the international market has been encouraged by the Portuguese Crown. Currently, Brazil is the largest producer of this crop, followed by India and China, as well as the largest producer of sugar and sugarcane ethanol, being responsible for more than 50% of the sugar sold worldwide. Although just over 50% of production is concentrated in São Paulo, the crop is grown in all regions of the country (Conab, 2015). When a high spatial concentrated occurs, there are environmental, economic and social impacts associated with sugarcane and suggests that these impacts can be positive or negative depending on the environment, the production model, and perhaps most importantly, the quality of management (Hess *et al*., 2016). Due to technological advances of Brazilian agriculture, irrigation has been widespread and efficient irrigation management is necessary to meet the water requirements of the crop, which is controlled by factors related to the agricultural and environmental system of the plant (Marin *et al*., 2016). Therefore, the estimated water consumption by sugarcane is highlighted in the search to maximize production with low costs (Knox *et al*., 2010). Ultimately, this approach also allows the improvement of growth models of crop, since algorithms that are normally available for plant transpiration simulation are relatively poor in view of the limitation of basic data involving the sap flow and stomatal response to the environment. One option for estimating crop transpiration is the Penman Monteith model (Monteith, 1965) and the input values can be appropriately adapted for each crop. The implementation of the PM model is recommended because it is a physical-mathematical mechanistic model that dispenses empirical accommodation in its development and which can be applied to any type of evapotranspirant surface. This model is interesting because it allows the study of some eco-physiological aspects of crops when it is applied in practice, especially where drip irrigation systems are used, where evapotranspiration is not so important (Marin *et al*., 2003a). The plant transpiration is a component of the energy balance which influences the temperature of the system, with particular effects on the leaf tissue according to anatomical factors of the leaves (size, pigmentation and mass), environmental factors (solar radiation, wind speed, air temperature and humidity), and biological factors that

---

****Corresponding author:*** **Kassio S. Carvalho,**
University of São Paulo (USP), College of Agriculture "Luiz de Queiroz" (ESALQ), Piracicaba-SP, Brazil.

determine the number and distribution of stomata (Leuzinger *et al*., 2010). The literature demonstrates that as the water becomes limiting, transpiration is reduced, with increased leaf temperature occurring due to the absorption of solar radiation (Wang and Gartung, 2010). Despite the long-term research into transpiration, modeling is not a trivial task, especially with the various determinants affecting it. Monteith (1965) proposed the big leaf model model and this is still a paradigm for the biophysical modeling of this process. According to this model, the transpiration of well watered plants could be modeled based on four main variables: the canopy energy balance (Rnef), the aerodynamic resistance (ra), the canopy resistance to vapor diffusion (rc) and the vapor pressure deficit in the crop environment (Δe).

Based on the literature, it can be assumed that rc is an important variable in the control of leaf transpiration, but this has not been extensively studied in sugarcane. Even in other crops, the relatively small number of rc studies is due to its high variability spatiotemporal and instrumental difficulty with measurements. Currently, the availability of equipment for the direct measurement of plant transpiration with sap flow sensors (Marin *et al*., 2008), in combination with porometers, allow it to be characterized sufficiently so that sub-models can be developed for the estimation of rc without direct measurement (Marin *et al*. 2003a). Regarding ra, it is still difficult to study this under field conditions due to the lack of instruments available for this type of analysis, such as wind tunnels or large micrometeorological profiles. Studies on Rn are relatively simple for crops with continuous coverage of the ground, since it can be measured with a balance-radiometer at relatively low cost, thus allowing the development of specific methods for estimating Rn (Pilau and Angelocci, 2016). The Δe is also easier to determine, as this can be assessed through simple temperature and vapor pressure measurements. Assuming that these four variables are properly arranged in the big leaf model, it is possible to parameterize general models for estimating soil evaporation and transpiration from plants instead using crop coefficient (Kc) approach (Allen *et al*., 1998). Examples of this approach have been reported for lemon (Daamen *et al*. 1999; Marin *et al*., 2003a), which resulted in good water used estimates for improving irrigation management, with less uncertainty about the use of Kc. Depending on the crop, one can use known models to estimate evaporation, as for sugarcane (Armour *et al*., 2013), associated with the PM model to determine evapotranspiration. This study aimed to apply the PM model for transpiration combined with a method for estimating soil evaporation.

MATERIALS AND METHODS

Experimental area

The study was conducted in sugarcane second ratoon. The planting was performed on October 2012 in line with single spacing 1.40m between rows of variety RB867515, distributing 13 to 15 buds per meter to a depth of 0.25 m and an area of 2.5 ha. The experimental area is located in Piracicaba, State of São Paulo - Brazil, at 540 amsl. The climate is characterized as Cwa, according to Koeppen classification and the soil is Dystrophic Udic Oxisol. The area was irrigated by a central pivot and controlled according to the data collected by the portable device soil moisture monitoring (Diviner 2000®. The irrigation management were performed whenever the soil reached 80% of the available water field capacity. Crop and fertilization treatment were performed in accordance with conventional practices used in the state of São Paulo.

Radiation Balance in canopy

To determine the net radiation effectively absorbed by sugarcane (Rnef), we used the methodology of Daamen *et al*. (1999), as shown in (Equation 1):

$$Rn_{ef} = \frac{[\mathrm{Rn_{ac.}}(1\text{-}\mathrm{e}^{-\mathrm{k.LAI}})]}{LAI} \qquad (1)$$

where Rnef is the balance of radiation effectively absorbed by the canopy (W m^{-2} leaf); Rn_{ac} is the net radiation above the canopy (W m^{-2}), which was measured by a net radiometer (Kipp Zonen, model NR-Lite) or estimated from solar radiation; k is the extinction coefficient by leaf area index unit (dimensionless); LAI is the leaf area index, measured by a plant canopy analyzer sensor (LAICOR, LAI-2000).

Aerodynamic resistance

The aerodynamic resistance (ra) was determined according to Stokes *et al*. (2016) (Equation 2).

$$ra = \frac{(ln((z2 - 0{,}7.zc))^2}{u2.k^2} \qquad (2)$$

where ra is aerodynamics resistance given in m s^{-1}; z2 is the height of 10 m above the ground, zc is the crop height, k is the von Karman constant (equal to 0.41) and u2 is the wind velocity adjusted to 10 m (Equation 3).

The PM method uses the measured wind speed at 2m and determines the aerodynamic resistance to vapor flow according to the difference between the height of the crop and height wind speed measurement (Equation 2). Sugar cane canopy can easily reach more than 2m height; therefore, the wind velocity (u2) was adjusted for a 10m height using the wind profile equation (Inman-Bamber & McGlinchey, 2003; Stokes *et al*., 2016):

$$\mathrm{u}_2 = \frac{\dfrac{u_{1.}ln\;((z_2\; - d_r)}{z_{or}}}{\dfrac{ln\;((z_1 - d_r)}{z_{or}}} \qquad (3)$$

where u1 and u2 are the wind speeds at 2m and 10m (m s^{-1}) by an automatic weather station located within 500m from the experimental field; Z_1 and Z_2 are the heights of 2 to 10 m above the ground; dr is the zero plane displacement of the reference surface = 0.07 m; and Z_{or} is the length of the reference surface roughness = 0.013 m.

Air vapor pressure deficit in the crop environment

For development purposes and evaluation of this approach, the leaf temperature was measured at three plants of each treatment by thermocouples (AWG 24, type T) at three expanded leaves (youngest, middle aged and older leaf) in order to capture any temperature gradient within the canopy in all leaves of each plant to solve Equation 4. The leaf temperature measures were made by juxtaposing a fine thermocouple fixed on the bottom side of leaves with 3M Micropore® tape on the intermediate portion of the leaf blade. Each thermocouple was connected to a datalloger Campbell Scientific, Inc. In addition to the leaf temperature, all weather variables necessary for determining rc were measured every second end with an average of every 15 minutes; this was also the frequency for measuring and storing wind speed data and sap flow. In order to evaluate the performance of Equation 4, we developed an algorithm to estimate leaf temperature iteratively programmed as described by Marin *et al.* (2003b).

$$Rn_{ef} - \frac{\rho.\mathrm{cp}.(\Delta e)}{\gamma.(\mathrm{rc}+\mathrm{ra})} - \frac{\rho.\mathrm{cp}.(\mathrm{Tf}-\mathrm{Ta})}{\mathrm{ra}} = 0 \qquad (4)$$

where Rnef is the net radiation effectively absorbed by the canopy (W m^{-2} leaf); ρ is the air density (kg m^{-3}); cp is the specific heat of dry air (J $kg^{-1}K^{-1}$); γ is the psychrometric coefficient (°C^{-1} 0.062 kPa); Tf is the leaf temperature (°C); Ta is the air temperature (°C); ra is the aerodynamic resistance the vapor and sensible reat diffusion (s m^{-1}) (Equation 2); rc is the coverage resistance vapor diffusion (s m^{-1}) (Equation 13); and Δe is the vapor pressure deficit of air in the crop environment (kPa) given by:

$$\Delta e = e_f - e_a \qquad (5)$$

Here, being ea the actual air vapor pressure (kPa), ef, the actual vapor pressure stomatal cavity (kPa), and is considered equal to the vapor saturation pressure at the leaf temperature due to the relative humidity value inside the leaf being very close to 100% (kPa). This was determined every 15 minutes by Equations (5) and (6):

$$e_a = \frac{e_f.UR}{100} \qquad (6)$$

$$e_f = 0{,}6110^{\frac{(7{,}5\,Tf)}{(237{,}3+Tf)}} \qquad (7)$$

Canopy resistance

In order to evaluate the performance of the estimation, the rc submodel and possible Equation settings (13) were measured from November 2014 until April 2015, once a month; Canopy resistance was measured with a dynamic balance porometer (Delta T model, AP4), properly calibrated periodically. Each day on which measurements were carried out, there were 5 sequences of measurements with average intervals of 2 hours between readings; sampling included 7 leaves, always on the same plants, and leaf position +1. Each reading sequence took no than 15 minutes. With these data, and the micrometeorological measurements, daily variation curves of the measured average values and the estimates obtained with Equation 13 were made. Such relationships were based on temperature and humidity, and wind speed and solar radiation data, measured in the experimental area. Due to the inherent characteristics of the biophysical process of stomatal regulation being very variable in the same plant, and appropriate considerations made by Alves and Pereira (2000) regarding the most appropriate approach for rc, we propose studying an alternative way to estimate rc. This proposition is based on the approach used by Monteith (1965) in the description of the Model Great leaf ("Big-leaf model") and assumes that the vegetation acts as if it were a single large leaf, with a balance of effective radiation (Rnef) and certain resistance to vapor diffusion (rc), has been tested in coffee and citrus with good performance (Marin *et al.*, 2003a; Marin *et al.*, 2016), can then describe the energy balance this coverage with (Equation 8):

$$\mathrm{Rn_{ef}} = \mathrm{H} + \mathrm{LE} \qquad (8)$$

where Rnef is the balance of effective radiation of vegetation cover (W m^{-2} leaf) (Equation 1), and H is the heat flow density sensitive between cover and an atmosphere (Wm^{-2} leaf), given by (Equation 9):

$$\mathrm{H} = \frac{\rho.\mathrm{cp}.(\mathrm{T_f}-\mathrm{T_{ar}})}{\mathrm{ra}} \qquad (9)$$

LE is the latent heat flux density from the canopy (W m^{-2} leaf) given by Equation 10:

$$\mathrm{LE} = \frac{\rho.\mathrm{cp}.(\mathrm{e_f}-\mathrm{e_{ar}})}{\gamma.(\mathrm{rc}+\mathrm{ra})} \qquad (10)$$

Substituting Equations 9 and 10 in Equation 8, we have:

$$\mathrm{Rn_{ef}} = \frac{\rho.\mathrm{cp}.(\mathrm{T_f}-\mathrm{T_{ar}})}{\mathrm{ra}} + \frac{\rho.\mathrm{cp}.(\mathrm{e_f}-\mathrm{e_{ar}})}{\gamma.(\mathrm{rc}+\mathrm{ra})} \qquad (11)$$

To simplify the Equation (11), we assumed the average temperature of vegetation is equal to the air, Equation 11 summarizes Equation 12, so that rc is obtained (Equation 13):

$$\mathrm{Rn_{ef}} = \frac{\rho.\mathrm{cp}.(\mathrm{e_f}-\mathrm{e_a})}{\gamma.(\mathrm{rc}+\mathrm{ra})} \qquad (12)$$

$$\mathrm{rc} = \frac{\rho.\mathrm{cp}.(\mathrm{e_f}-\mathrm{e_a})}{\gamma.Rn_{ef}} - \mathrm{ra} \qquad (13)$$

Equation 13 thus provides an estimate of rc for a amphistomatic leaf, from weather variables that are easy to measure and aerodynamic resistance. At night, the rc was considered equal to 2500 m s^{-1}, as described by Nobel (1999), in order to simulate the nocturnal stomatal closure. Moreover, early in the morning a few days, when the relative humidity was close to 100%, there was the occurrence of rc values <0 indicating the presence of free water on the leaves and allowing the inference that only aerodynamic resistance controlled the evapotranspiration process. Thus, at times when Equation 13 provided rc values <0 and Rn > 0, we assumed rc = 0 s m^{-1}.

Penman-Monteith model

The sugarcane estimated transpiration was assessed using the PM model (Monteith, 1965) adapted to hypostomatic leaves, as shown in Equation 14 for a 15 minute period. The data estimated by the model were integrated to periods of 24 hours, considering the Rnef values equal to zero during the night, thus obtaining plant transpiration by aerodynamics using the equation. For comparison purposes, the model was also used for data during the daytime considering null transpiration at night.

$$\lambda T = Af.\frac{s.\,Rnef + \rho.\,cp.\,\frac{(\Delta e)}{ra}}{s + \gamma.\,(1+\frac{rc}{ra})} \tag{14}$$

where, T is the crop maximum transpiration of sugarcane (mm $15min^{-1}$); Rnef is the balance of effective radiation canopy (MJ m^{-2} of leaf $15min^{-1}$) (Equation 1); Af is the leaf area of the cane field (m^2); λ is the latent heat of water vaporization (MJ kg^{-1}); ra is the aerodynamic resistance vapor diffusion (s m^{-1}) (Equation 2); rc is the canopy resistance for vapor diffusion (s m^{-1}) (Equação13); ρ is the air density (kg m^{-3}); cp is the specific heat of dry air (J $kg^{-1}K^{-1}$); γ is the psychrometric coefficient ($°C^{-1}$ 0.062 kPa); Δe is the vapor pressure deficit of air (kPa) (Equation 5) and s is the slope of the vapor pressure curve determined by the following expression:

$$s = \frac{4098.\,e_s}{(Ta + 237{,}3)^2} \tag{15}$$

Sap flow

In order to evaluate the estimated transpiration yielded by PM model, transpiration with was determined sap flow sensors was determined by the heat balance method with Dynamax Inc. sensors. Three sensors were installed in the stalks of sugar cane in the region of internodes in order to prevent the sprouting of stem buds. The measurements were performed for 47 days. The sap flow calculation was based on the heating segment stem for a heat source (P), and the thermal energy was dissipated by driving in axial shafts (Qi and Qs) and radial (Qr) convection and also in through the sap flow (QF). The sap flow (FS), was obtained by (Equation 16), as described by Sakuratani and Abe (1985):

$$FS = \frac{P - Qa - Qr}{dT.cp} \tag{16}$$

where FS is the sap flow in kg s^{-1}; P is the applied power (W); Qa (Qs + Qi) is the flow in watts of energy dissipated axially; data by summing the upper axial flow (Qs) and lower (Qi); Qr is the flow of energy dissipated radially; dT is the temperature difference between the upper and lower end of the sensor; and cp is the specific heat of water ($4{,}186 \times 10^{-3}$ J kg^{-1} $°C^{-1}$).

Axial flow (Qa) was obtained by Equation 17:

$$Qa = Kst.Ac\frac{(\Delta Tb - \Delta Ta)}{\Delta x} \tag{17}$$

where Kst is the thermal conductivity of the stem, which is considered 0.54 Wm^{-1} $°C^{-1}$ (Sakuratani & Abe, 1985), Ac is the area of the cross section of the stem (average plant $7{,}694 \times 10^{-4}$ m^2) and Δx is the distance between the thermocouples (3 mm).

The radial flow (Qr) was calculated according to Equation 18:

$$Qr = Kr * \Delta Trad \tag{18}$$

where Kr is the radial thermal conductivity of the heat meter and can be obtained under conditions of null or despicable sap flow sensor for each installation, as shown in Equation 19:

$$Kr = (P - Qa)\ \Delta Trad \tag{19}$$

The determination of Kr was performed with data collected between 3 and 5 am, a time considered zero sap flow or close to zero. The evaluation of the data for high and low sap rising rates followed the approach described by Marin *et al.* (2008). Transpiration obtained from the sap flow sensors was integrated to obtain the results in (L $stalk^{-1}$ d^{-1}). Immediately after this procedure, leaf area of each stem was measured and water loss per square meter of leaf day was estimated; this was multiplied by the area in question, finding the consumption of water by mm crop. The average number of leaves on the stem when sap flow was measured was 0.34 m^2 $plant^{-1}$.

Soil water evaporation

The soil water evaporation was estimated following the approach described by Armour *et al.* (2013) (Equation 20):

$$Es=ETo((min(\frac{(\theta_C-\theta_{AD})}{(\theta_S-\theta_{AD})},1))^3\ (0.05+exp(-0.38LAI)-c)-0.1(1-exp(-0.38LAI))+0.1)) \tag{20}$$

where ETo is the reference evapotranspiration (Allen *et al.*, 1998); θC, θAD and θS, were the current soil water contents (θC), free air dried soil water content (θAD) and water content at saturation (θS), respectively; and c is the fraction of soil covered with sugarcane trash, which was assumed to 0.8 in this simulation.

Crop evapotranspiration

Sugarcane actual evapotranspiration (ETc in mm d^{-1}) is the sum of soil evaporation and potential transpiration or root water supply whichever is the least (Equation 21).

$$ETc = (Es+T) \tag{21}$$

ETc Bowen ratio method

A Bowen ratio method was used to evaluate the mass and energy exchanges over the field with two forced ventilation psychrometers (Marin *et al.* 2001b). Measurements of dry and wet temperatures (°C) were performed, with a height difference of 1 m between them, with the lower measurement maintained at canopy level, following sugarcane plant growth. A net radiometer and two soil heat flux instruments were also installed. The crop evapotranspiration was determined according to (Equation 22):

$$LE = \frac{Rn - G}{1 + \beta} \rightarrow ETc = \frac{Rn - G}{\lambda(1 + \beta)} \tag{22}$$

where Rn is the net radiation (MJ m^{-2} d^{-1}), G is the soil heat flux (MJ m^{-2} d^{-1}), β is the Bowen ratio, LE is the latent heat flux (MJ m^{-2} d^{-1}), and λ is the latent heat of evaporation.

The Bowen ratio values (β) were calculated for each 15 min interval based on the temperature gradient values (ΔT), the vaporvapor pressure gradient values (Δe) and psychometric constant (γ), according to (Equation 23):

$$\beta = \gamma \frac{\Delta t}{\Delta e} \quad (23)$$

The Bowen ratio method can show some variability in values, which were checked according to Perez *et al.* (1999). In periods when the measures had such variability, interpolations were done. When periods exceeding 2 h of such undesired variability, the whole day data were was discarded. Only day time data were used to compute ET from BRM method.

RESULTS AND DISCUSSION

Canopy Radiation Balance

Figure 1 shows the variation curves of the effective radiation balance of sugarcane (Rnef), the radiation balance of a lawn (Rn), net radiation from above the sugarcane canopy (Rnac) and global net radiation (Qg) over one day. Rn, Rnef and Rnac accompanied the available Qg radiation. It should also be noted that on DAR 268, around noon, the maximum values of Qg, Rn, Rnef and Rnac were shown. Similar results were obtained by André *et al.* (2010), who attributed this to the lower angle of sunlight, causing greater penetration and retention of radiation inside the plant. This higher incidence of radiation for 14 hours also favors the reduction of rc (Figure 5) and consequently increases transpiration in sugarcane.

Figure 2 shows the net radiation of a lawn, the effective radiation balance in the cane field (a) and net radiation above the cane (b).

Figure 3 shows the relationship between the global radiation balance and Rnef and Rnac (a) and (b), respectively. Note that in both Figure 3a and Figure 3b, this was represented by a linear regression equation, with the determination coefficient of 0.86 for (a) and 0.84 for (b). This shows that Rnef and Rnac increase to the extent that Qg increases. Knowing this relationship is important since it is not common to determine Rnef and Rnac on farms and Qg is easily found in weather stations, thus favoring the calculation of crop evapotranspiration by the PM method.

Aerodynamic resistance

Figure 4 shows the relationship between the aerodynamic resistance estimated with the Stokes *et al.* (2016) model and wind speed adjusted to 10 m. Note that the relationship was adjusted by a power model with a determination coefficient of r^2=0.99. This shows that the wind speed heavily interferes with ra even for a relatively smooth and uniform canopy such as sugarcane. In the sugarcane crop, where the canopy is closed and ra is high for most of the crop growth, it is important to take into consideration the effect of ra on transpiration when scale and parameterizing the canopy, mainly for transpiration models that do not fully use the PM model (Stokes *et al.*, 2016). These authors point out that the effect of closing the stomata on transpiration depends on the stomatal resistance and aerodynamic resistance. When the stomatal resistance is large relative to the aerodynamic resistance, a reduction in stomatal conductance occurs with an increasing CO_2 concentration, which is reflected by a reduction of transpiration.

Canopy resistance to vapor diffusion

Comparing the estimated rc values with the hourly average of observed rc it is verified that the model is related to the rc values measured in the field (Figure 5). By analyzing the measured and estimated values throughout the day, it can be seen that the values were very different on 12/08/2014, in which we infer that the water stress might be the main cause for such difference, since irrigation equipment did not work for some days and let for crop to be under drought stress increasing the rc. Another factor that should be taken into account when analyzing the canopy resistance is the difficulties associated with rc modeling and the problems originating in the measurement with the porometric technique, as well as by representative sampling of difficult leaves in the entire plant. Moreover, this variability is commonly found in rc measures in the field as a result of different exposure conditions of the leaves to sunlight and wind, internal physiological conditions of leaves and temporal fluctuation of the stomatal aperture (Marin *et al.*, 2003b). The rc values tended to be minimal from 12 to 14 hours; this may have occurred due to higher temperatures and solar radiation at this time (Figure 1). Nassif *et al.* (2014) also found that on days with a higher incidence of radiation, there is a rapid reduction of rc, reaching its peak around noon. In the afternoon period, there was a mild and steady increase, which was attributed to cloudy days and less sunlight. Furthermore, according to Marin (2003b), the effect of high foliar temperatures, and indirectly Δe, have an important role in stomatal regulation, because the leaves are very sensitive to environmental conditions therefore affecting its water relations. During most of the measurement days, sugarcane rc was above 500 s m^{-1}, indicating some resistance to the transpiration process. Throughout the cycle, the ra values were mostly lower than rc, indicating that changes in LE affecting turbulent mechanisms were more effective compared to vapor transfer from the crop canopy (Silva *et al.*, 2013).

Figure 6 shows the relationship between the measured rc data and that estimated by means of estimation by the proposed rc model. It appears that the model has to relationship with the rc values measured in the field, with a coefficient of determination of r^2=0.62. Note that the model presented a satisfactory performance because it is very difficult to use rc to estimate models because it changes throughout the day.

Canopy temperature

By quantifying the canopy temperature, using equations 5, 6 and 7, it was possible to determine specific Δe values for the sugarcane crop. This variable also plays a significant role in quantifying the crop water consumption since when transpiration is reduced, an increase in the temperature of the cover occurs and therefore Δe also tends to increase. The applied approach well estimated the estimating the canopy temperature was with a high correlation (r^2=0.84) between observed and simulated data (Figure 7a and 7b). This model was also used by Marin *et al.* (2003b) to estimate the lawn temperature with good performance and r^2=0.79.

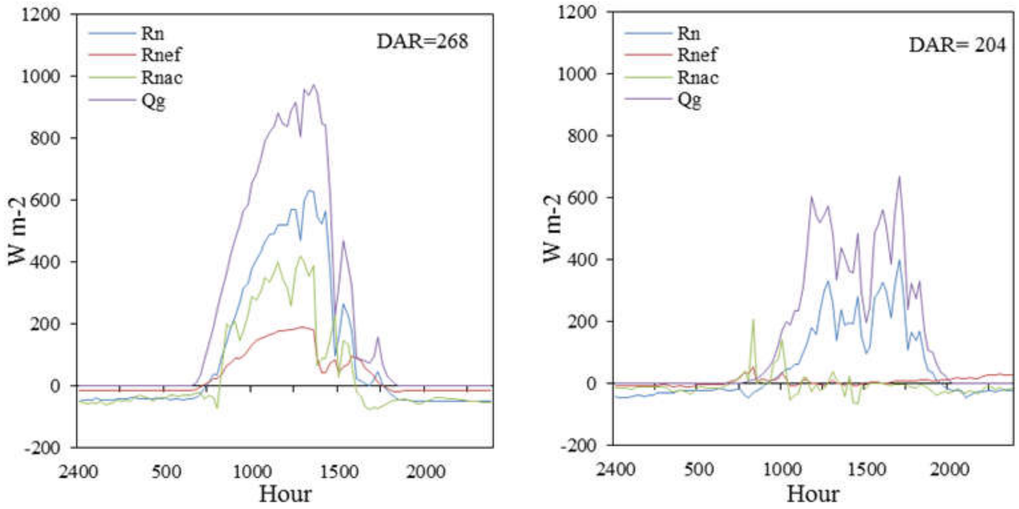

Figure 1. Hourly evolution of the Rn, Rnef, Rnac and Qg on a day with a high incidence of radiation, DAR 268 (a), and on a cloudy day, DAR 204 (b)

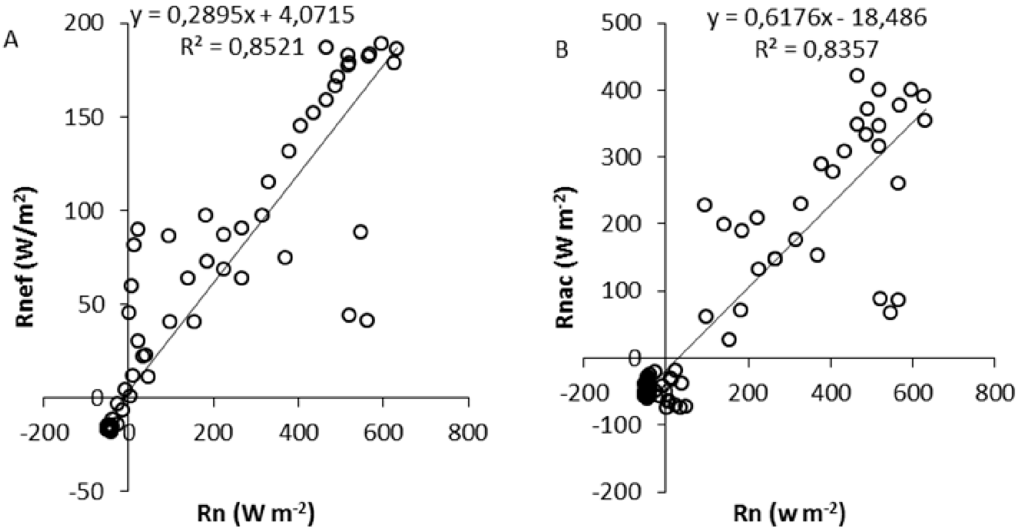

Figure 2. Relationship between the balance of net radiation of a lawn and the balance of effective radiation from the cane field (a) and the net radiation above the cane field (b)

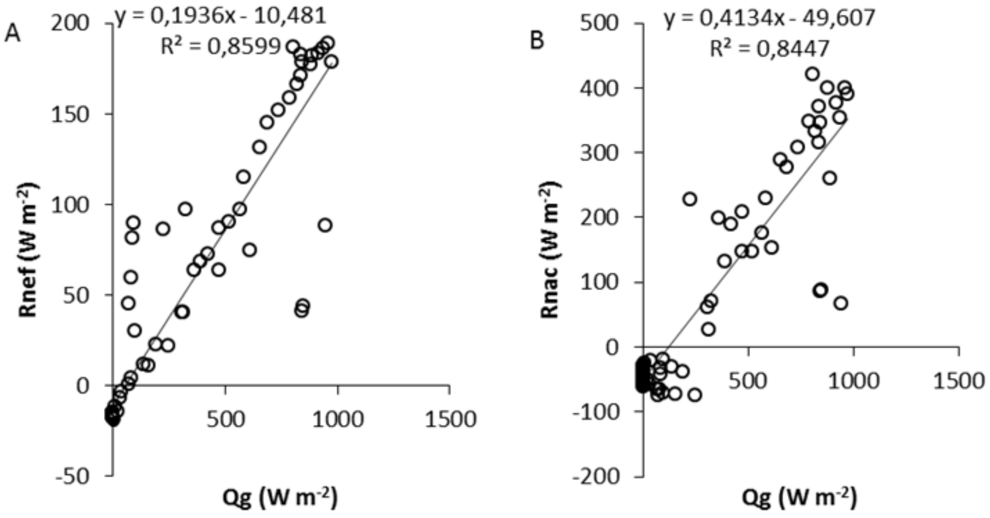

Figure 3. Relationship between the balance of global radiation (Qg) and the balance of effective radiation from the cane field (a) and the net radiation above the cane field (b)

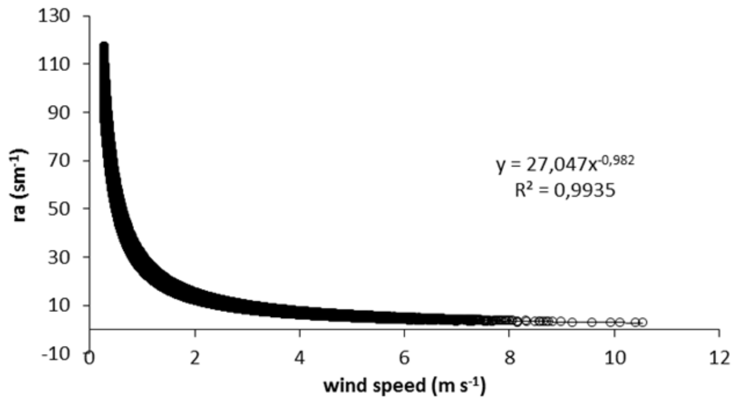

Figure 4. The relationship between aerodynamic resistance values estimated by the model of Stokes *et al*. (2016) with wind speed adjusted at 10 m

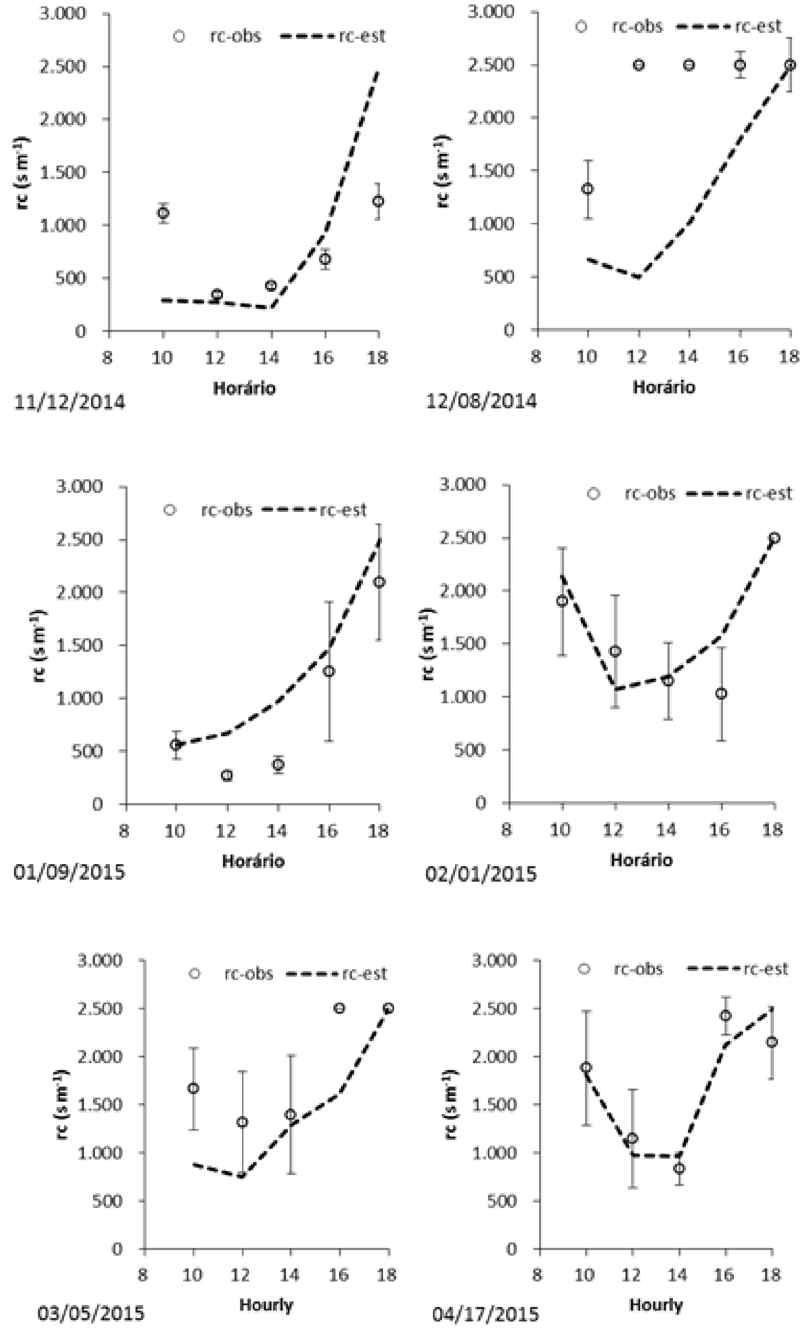

Figure 5. Hourly variation of stomatal resistance measurements of a cane field (rc-obs) in relation to the estimated stomatal resistance (rc-est) in the months of November (a) and December (b) 2014 and January (c), February (d), March (e) and April (f) 2015, Piracicaba - Brazil

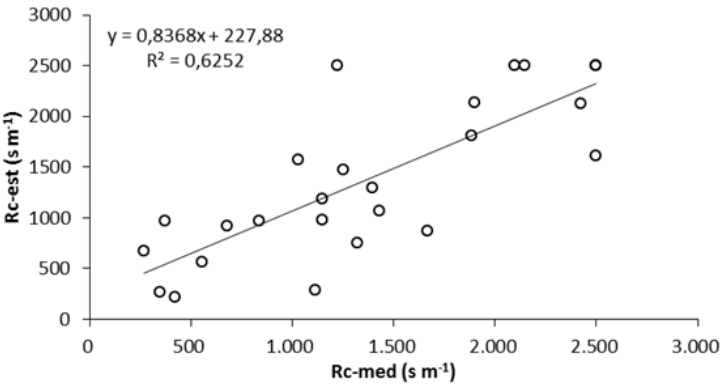

Figure 6. Relationship between stomatal resistance observed and stomatal resistance estimated in second ratoon sugarcane

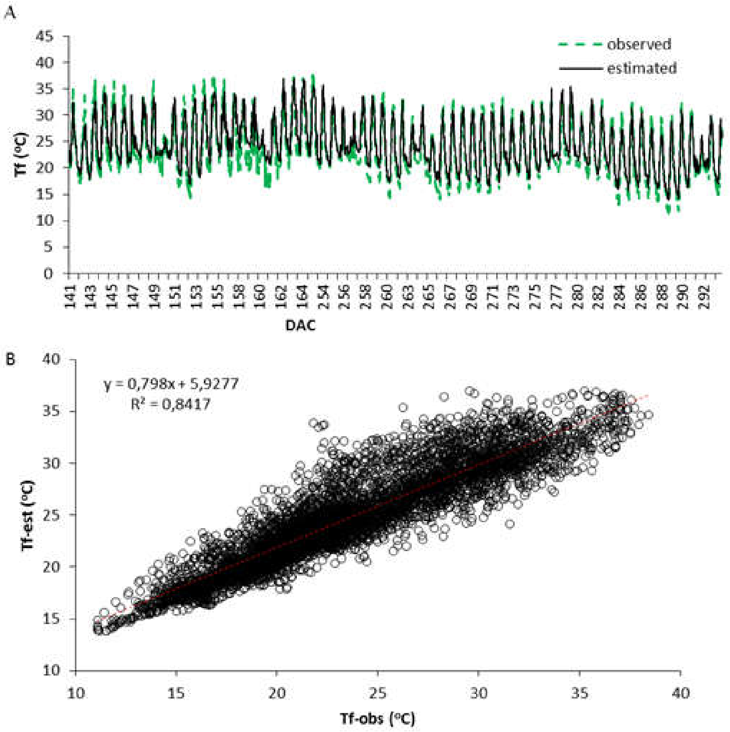

Figure 7. Temperature range of coverage of the estimated sugarcane and observed in relation to the days after ratooning (DAR) (a) and the relationship between the measured (Tf-obs) and estimated (Tf-est) temperature (b)

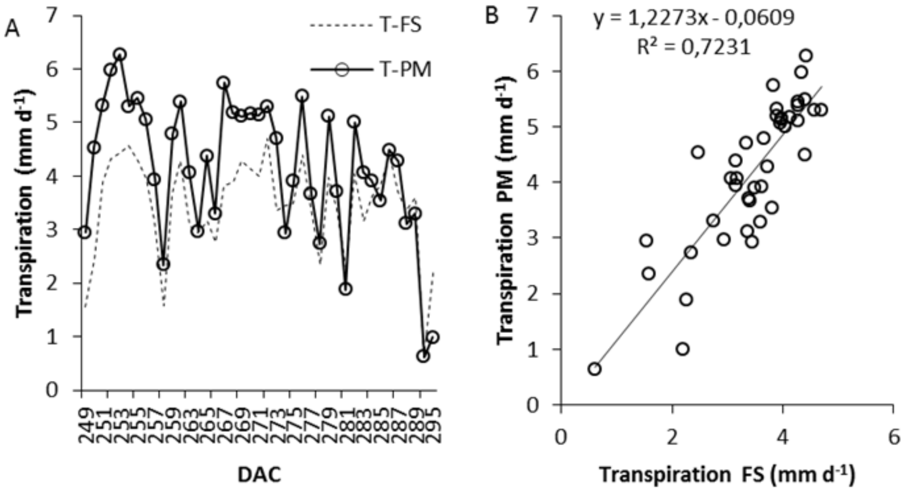

Figure 8. Change in transpiration estimated and measured over several days after ratooning (DAR) (a) and the relationship between that estimated with the Monteith model (1965) and observed with sap flow sensor (b)

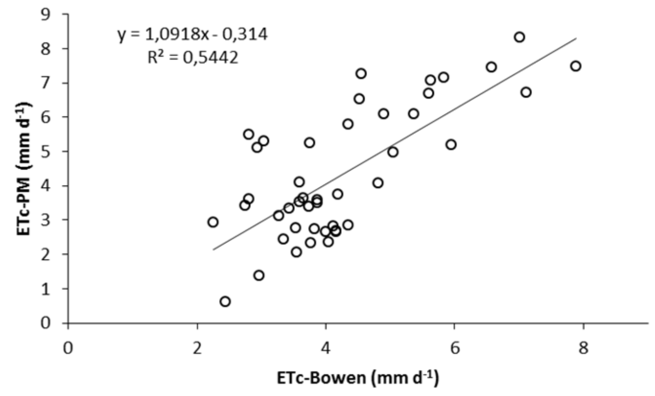

Figure 9. Relationship between ETc estimated based on the PM+Es model and observed with the BRM

Transpiration

The determination of the maximum transpiration was estimated by the PM model, adapted to sugarcane; this showed high correlation with transpiration measured using sap flow sensors. However, it is verified that the PM model overestimates transpiration when compared with measurements. It is also noted that the transpiration estimated by the PM model ranged from 0.6 to 6.3 mm d^{-1}, with an average of 4.17 mm d^{-1}, and transpiration measured by sap flow sensors ranged from 0.6 to 4.7 mm d^{-1} with an average transpiration in the period of 3.45 mm d^{-1} (Figure 8). Despite there being an overestimation of transpiration for a few days, it is noted that by adding the soil water evaporation, estimated crop evapotranspiration values were similar to those measured with the BRM (Figure 9). Chabot *et al.* (2005), by measuring the transpiration of sugarcane (variety CP 66-345) with sap flow sensors in semi-arid region of Morocco, a, found the total transpiration to be 8 mm d^{-1} in average for a reference transpiration ETo=5 mm d^{-1} in the same period. The authors attributed this high transpiration to possible errors such as related sap flow measurements from sensors or extrapolation from some stems throughout the canopy. Anyway, it is interesting to see how high transpiration rates can be observed in well-watered sugarcane plantation.

Crop evapotranspiration

By analyzing the relationship between crop evapotranspiration (ETc) estimated by the PM method and measured with the BRM, it was found that the relationship presented r^2=0.54. Despite R^2 not being high, the angular coefficient (b) was very consistent, and close to 1 (Figure 9). Similar results were obtained by Silva *et al.* (2013), in which the ETc was low at the beginning of the cycle (as leaf area index (LAI) were low); during the course of the cycle, ETc reached maximum values of 6 to 8 mm day^{-1}. Nassif *et al.* (2014) also found ETc values for sugarcane in the region of Piracicaba to be above 7 mm d^{-1} and attributed this to the dry air masses, high temperature and solar radiation in the region, which result in high atmospheric demand for a well coupled sugarcane; when combined with water availability in the soil, this favors the increase in ETc. We found average ETc estimated based on the PM+Es model was 4.32 mm d^{-1} and the average ETc measured with the BRM was 4.25 mm d^{-1}. Similar values were obtained by Inman-Bamber & McGlinchey (2003), who found ETc average of 5.2 mm d^{-1} using the BRM and Silva *et al.* (2012), who found an average ETc of 4.7 mm d^{-1}, for semiarid condition on Brazilian.

Conclusion

The PM model showed consistent values for the transpiration crop of sugarcane. The water consumption of sugarcane can be well estimated according to atmospheric conditions and the input data (rc, ra, Rnef and Δe) with the PM model coupled with a soil evaporation method proposed. The approach is useful to estimate sugarcane ETc for improving crop water use estimates, irrigation management and process based crop models.

Acknowledgements

FAPESP and CNPQ for the financing of the project.

REFERENCES

Allen, R.G.; Pereira, L.S.; Raes, D.; Smith, M. *Irrigation and drainage.* Rome:FAO, 1998. 22p. (FAO. Irrigation and Drainage Paper, 56).

Alves, I.; Pereira, L.S. Modelling surface resistance from climatic variables? *Agricultural Water Management,* v.42, p.371-385, 2000.

André, R. G. B., Mendonça, J. C., Marques, V. D. S., Pinheiro, F. M. A., & Marques, J.. Aspectos energéticos do desenvolvimento da cana-de-açúcar. Parte 1: balanço de radiação e parâmetros derivados. *Revista Brasileira de Meteorologia*, v. 25, n. 3, p. 375-382, 2010.

Armour, J. D., Nelson, P. N., Daniells, J. W., Rasiah, V., & Inman-Bamber, N. G. Nitrogen leaching from the root zone of sugarcane and bananas in the humid tropics of Australia. *Agriculture, ecosystems & environment*, v. 180, p. 68-78, 2013.

Chabot, R., Bouarfa, Sca., Zimmer, D., Chaumont, C., & Moreau, S. 2005. Evaluation of the sap flow determined with a heat balance method to measure the transpiration of a sugarcane canopy. *Agricultural Water Management*, 75(1), 10-24.

Companhia Nacional de Abastecimento. Acompanhamento de safra brasileira : cana-de-açúcar, segundo levantamento, agosto/2013.Brasília : *Conab*, 2015.

Daamen, C.C.; Dugas, W.A.; Prendergast, P.T.; Judd, M.J.; Mcnaughton, K.G. Energy flux measurements in a sheltered lemon orchard. *Agricultural and Forest Meteorology*, v.93, p.171-183, 1999.

Hess, T.M., Sumberg, J., Biggs, T., Georgescu, M., Haro-Monteagudo, D., Jewitt, G., Ozdogan, M., Marshall, M., Thenkabail, P., Daccache, A., Marin, F., Knox, J.W., 2016. A sweet deal? Sugarcane, water and agricultural transformation in Sub-Saharan Africa. *Global Environmental Change* 39, 181–194. doi:10.1016/ j.gloenvcha.2016.05.003

Inman-Bamber, N.G.; McGlinchey, M.G. Crop coefficients and water-use estimates for sugarcane basedon long-term Bowen ratio energy balance measurements. *Field Crops Research***,** Amsterdam, v. 83 n. 1, p. 125-138, 2003.

Knox, J.W., Rodríguez Díaz, J.A., Nixon, D.J., Mkhwanazi, M., 2010. A preliminary assessment of climate change impacts on sugarcane in Swaziland. *Agricultural Systems* 103, 63–72.

Leuzinger, S.; Vogt, R.; Körner, C. Tree surface temperature in an urban environment. *Agricultural and Forest Meteorology*, Amsterdam, v.150, p.56-62, 2010.

Marin, F. R., Angelocci, L. R., e Villa Nova, N. A. Estimativa da transpiração máxima de lima ácida, cv. Tahiti, pelo modelo de Penman-Monteith. *Revista Brasileira de Agrometeorologia*, Santa Maria, v. 11, n.2, p. 237-243, 2003a.

Marin, F. R., Angelocci, L. R., Nassif, D. S., Costa, L. G., Vianna, M. S., & Carvalho, K. S.. Crop coefficient changes with reference evapotranspiration for highly canopy-atmosphere coupled crops. *Agricultural Water Management*, v.*163*, p.139-145, 2016.

Marin, F. R.; angelocci, L. R.; Coelho Filho, M. A.; Villa nova, N. A. Construção e avaliação de psicrômetro aspirado de termopar. *Sci. agric*., Piracicaba, v. 58, n. 4, 2001b.

Marin, F. R.; Righi, Evandro Zanini ; Santiago, A. V. ; Sentelhas, Paulo Cesar ; Maggioto, S. R. ; Lyra, G. B. . Estimativa da temperatura da superfície e da evapotranspiração em gramado com um método iterativo. *Revista Brasileira de Agrometeorologia*, Santa Maria/RS, v. 11, n.2, p. 221-228, 2003b.

Marin, F.R.; Ribeiro, R.V.; Angelocci, L.R.; Righi, E.Z. Fluxo de seiva pelo método de balanço de calor: base teórica, qualidade das medidas e aspectos práticos. *Bragantia*, Campinas, v. 67, n. 1. p. 1-12, 2008.

Monteith, J.L. Evaporation and Environment. *Symposium of Society of Experimental Biology*. v.19, p.205-234, 1965.

Nassif, Daniel SP; Marin, Fabio R.; Costa, Leandro G. Evapotranspiration and transpiration coupling to the atmosphere of sugarcane in southern Brazil: scaling up from leaf to field. *Sugar Tech*, v. 16, n. 3, p. 250-254, 2014.

Nobel, P.S. *Physicochemical and Environmental Plant Physiology*. San Diego: Academic Press, 1991. 635 p.

Pilau, F.G., Angelocci, L.R. Padrões de interceptação de radiação solar por cafeeiros em função da área foliar. *Coffee Science* 11, 127–136, 2016.

Sakuratani, T.; ABE, J. A heat balance method for measuring water sap flow in the stem of intact plants and its application to sugarcane plants. *Japan Agricultural Research Quarterly*, Tsukuba, v.19, n.2, p.92-97, 1985.

Silva, T. G. F., Zolnier, S., Moura, M. S. B., & Souza, L. S.. Sazonalidade do Controle de Evapotranspiração pela Cana-de-Açúcar Irrigada e Características Aerodinâmicas da Cultura no Semiárido brasileiro. *Revista Brasileira de Geografia Física*, v. 6, n. 4, p. 621-634, 2013.

Silva, T. G., de Moura, M. S., Zolnier, S., Soares, J. M., Vieira, V. J. D. S., & Júnior, W. G. (2012). Requerimento hídrico e coeficiente de cultura da cana-de-açúcar irrigada no semiárido brasileiro. *R. Bras. Eng. Agríc. Ambiental*, v. 16, n. 1, p. 64-71, 2012.

Stokes, C. J., Inman-Bamber, N. G., Everingham, Y. L., & Sexton, J. Measuring and modelling CO 2 effects on sugarcane. *Environmental Modelling & Software*, v. 78, p. 68-78, 2016.

Wang, D.; Gartung, J. Infrared canopy temperature of early-ripening peach trees under postharvest deficit irrigation. *Agricultural Water Management*, Amsterdam, v.97, p.1.787-1.794, 2010.

****