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RESEARCH ARTICLE

The role of decoupling factor on sugarcane crop water use under tropical conditions

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Abstract

The expansion of sugarcane crop to regions with lower water supply in Brazil has increased the importance of correct estimation of crop water requirements. Currently, the irrigation management is generally done using the crop coefficient (*Kc*) based on the FAO 56 bulletin. *Kc* is used to determine the potential water demand of the crop for a given period of time and is considered constant for each crop stage. However, some recent studies have shown that *Kc* can be significantly variable under different evapotranspiration (*ETo*) rates. This paper aimed to analyse sugarcane water consumption at different scales: plant (sap flow measurements by energy balance method); canopy (Bowen ratio energy balance method); and plant–atmosphere coupling (infrared gas analyser) to reduce the uncertainties on the irrigation practices. Measurements were taken at two experimental sites, where a modern Brazilian cultivar CTC 12 was grown under drip irrigation and an old main Brazilian cultivar (RB867515) was grown under sprinkler irrigation by a central pivot. The mean crop evapotranspiration (*ETc*) values by the Bowen ratio energy balance method were 2.92 and 3.68 mm d^{-1} for RB867515 and CTC 12, respectively, resulting in a mean *Kc* of 0.99 at the full vegetative growth stage. *Kc* values were dependent on *ETo* and varied between 0.2 and 1.7 for both cultivars. This occurred in a crop coupled to the atmosphere ($\Omega = 0.37$) and was the same found in other coupled crops such as coffee and citrus. In conclusion, the sugarcane *Kc* for southeast Brazil presented temporal variability due to coupling conditions according to reference evapotranspiration, and this should be considered in irrigation management.

Keywords: Irrigation; Water use efficiency; Variable crop coefficient

Introduction

In Brazil, the sugarcane crop has become increasingly important during the past 10 years, mainly because of increasing ethanol, sugar and energy demands. Water-deficit stress is recognized as a limiting factor in most of the sugarcane growing regions in Brazil (Marin *et al.,* 2015). In some areas, irrigation is commonly needed to ensure minimum yield and to keep plants alive (Vianna and Sentelhas, 2015). Despite the importance of this crop, few studies have focused on water use by sugarcane crops in Brazil.

Currently, irrigation management is done by using crop coefficient (*Kc*). However, *Kc* is affected by changing climate conditions and changes during growth and ripening (Allen *et al.,* 1998). Under humid conditions with low wind speed, *Kc* is less dependent on aerodynamic variables and tends to the unity for most crops. The irrigation management for sugarcane is usually based on the FAO bulletin 56 issued to estimate *Kc*, which is different for early, middle and final growth (0.4, 1.25 and 0.75, respectively) stages. Some authors have reported that for maximum sugarcane crop growth, *Kc* values should range between 0.5 and 1.1 (Silva *et al.*, 2012), while Inman-Bamber and McGlinchey (2003) have reported *Kc* values between 0.5 and 1.4, depending on the radiation intercepted by the crop.

This variability arises from factors affecting the process of water loss that are not measured or considered in water consumption studies for homogeneous canopies such as sugarcane. The plant–atmosphere-related decoupling factor (Ω) (Jarvis and McNaughton, 1986) has a strong relation to the atmospheric water demand for many crops (Marin *et al.*, 2016; Pereira, 2004), including sugarcane. Jarvis (1985) has explained that the decoupling factor is a numerical index of plant–atmosphere interaction and is related to the crop aerodynamic (*ra*) and stomatal (*rs*) resistances, allowing to know the variation of physiological responses to different states of atmosphere, mainly photosynthesis and water use efficiency. Aerodynamic factors are more important for defining gas exchange under coupling conditions, while the incidence of radiation becomes more important under decoupling conditions.

According to Jarvis and McNaughton (1986), extrapolation of experimental data on plant water consumption can result in uncertainty due to scaling up or down. For example, Eksteen *et al.* (2014) have evaluated two sugarcane genotypes and found Ω to be between 0.187 and 0.968 with varying water availability. Therefore, in an attempt to reduce this source of uncertainty and to provide consistent data to improve sugarcane irrigation management, we used a set of measurement techniques at different scales for the assessment of water use in sugarcane crop.

Material and Methods

Experimental fields

Two experimental field trials were carried out at Piracicaba, Brazil (22.67°S; 47.64°W; 530 m a.s.l., both as Cwa Koeppen classification), with two sugarcane cultivars. In the first experimental area (EA1), we evaluated the first ratoon of CTC 12 cultivar planted in February 2010, with twin row spacing (0.5 × 1.5 m), grown in a Udox soil of 0.3 ha and harvested after 365 days (March 2012). This field received full subsurface drip irrigation without water deficit. In the second experimental area (EA2), we evaluated the plant cycle of RB867515 cultivar planted in 2012/13 growth season in an Ultisol soil (2 ha). A simple spacing (1.4 m) was used; the planting date was October 2012, and it was harvested after 365 days. This field received full sprinkling irrigation by a centre pivot, controlled by daily crop water balance with at least 80% of soil water-holding capacity.

Daily weather data (maximum and minimum air temperature, rainfall, air humidity, average wind speed, wind direction, global and net radiation) were collected every 15 min for both experiments throughout the crop cycle with the help of an Automated Weather Station (AWS) at 1 km from the experimental area. The AWS has been maintained following the World Meteorological Organization standards, and is composed of Campbell Scientific sensors: one pluviometer (TB4), one thermo-hygrometer (HMP-155), one wind speed and direction sensor (034A), one barometer (CS106), one rugged pyranometer (CM3), one net radiometer (NR-LITE2) and a quantum sensor (LI190SB).

Evapotranspiration, transpiration and decoupling factor methods and calculations

A Bowen ratio energy balance (BREB) method was used to evaluate the mass and energy exchange over fields with two forced ventilation psychrometers (Marin *et al.* 2001). In EA1, the fetch was 85 m from predominant wind direction (SE). In EA2, the fetch was 110 m from predominant wind direction (SE) and 90 m from other directions. When winds were from an unsuitable direction for this technique, with no good fetch, recorded data were discarded.

Measurements of dry and wet bulb temperatures (°C) were performed at two heights for the evaluation of latent and sensible heat fluxes from the sugarcane canopy. There was a height difference of 1 m between them, with the lower measurement maintained at least 0.5 m above canopy

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height and following sugarcane plant growth (Allen *et al.*, 2011). The BREB method data were collected from 30 April 2011 to 31 December 2011 at EA1 and between 14 February 2013 and 20 June 2013 at EA2. A net radiometer was installed 3 m above the canopy, and two soil heat flux sensors were also installed at 2 cm depth, on sugarcane rows and inter-rows. Crop evapotranspiration was determined according to Equation 1:

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

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, °C), vapour pressure gradient values (Δe, kPa) and psychometric constant (γ), according to Equation 2:

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

The BREB can show some variability in values, which were checked according to the methodology of Perez *et al.* (1999). When measures had such variability, interpolations were done. When periods exceeded 2 h of such undesired variability, the whole day's data were discarded. Only daytime data were used to compute evapotranspiration (*ET*) from the BREB method.

Sap flow (*SF*) measurements by the heat balance method (Sakuratani, 1981) were performed on four representative stalks (Eksteen *et al.*, 2014) at the internodes in both areas, which were used to evaluate the water use at the plant scale. We used non-invasive sensors with a constant heat source (Dynamax Sap Flow System, SGB25-WS, Houston, Texas). *SF* gauges were attached 30 cm above the soil surface, at the internode portion of the stem, to avoid interference of soil heat flow, as done by Eksteen *et al.* (2014). Leaves on this position were removed, and a thermal paste was used to ensure close contact between gauge and stem. Stems were changed every 10 days to reduce the chance of long-term heat damage and the sprouting of node roots. To avoid any interference of incident solar radiation, the sensors were coated with a reflective foil. *SF* was calculated using Equation 3 (Sakuratani and Abe, 1985):

$$SF = \frac{P - Qa - Qr}{dT * cp} \quad (3)$$

where SF is the sap flow (kg s^{-1}), P is the power applied (W), Qa is the axially dissipated energy (W), Qr is the radially dissipated energy (W), dT is the upper and lower temperature difference (°C) and cp is the specific heat of water (4.186 J kg^{-1} °C^{-1}).

The determination of thermal conductivity of the radial heat meter (Kr) was performed with collected data between 3:00 and 5:00 am, when *SF* was considered to be close to 0. In low *SF* conditions, the differences between temperature sensors were close to 0, which can lead to excessively high transpiration data (Marin *et al.*, 2008). The 24-h integrated values of *SF* were considered as representative of the daily transpiration of each plant. Transpiration rates were normalized to obtain a transpiration rate on a leaf area unit basis (mm m^{-2} of leaf). The crop transpiration was scaled up to a ground area unit basis by multiplying the average transpiration rate of the four plants by the average leaf area index determined using the gap-fraction method (LAI-2000, Li-Cor, Inc.).

Diurnal courses of stomatal conductance (gs) were measured during 5 days in the EA2 treatment with an infrared gas analyser (LCproT Advanced Portable Photosynthesis System, ADC) on the exposed leaves (the first leaf with an apparent dewlap) between 9:00 am and sunset (local time) in 10 plants. Values of gs were manipulated to be expressed as diffusive resistance (rs), and the decoupling factor (Ω) was computed for a hypostomatous leaf as defined by Equation (4) (Jarvis and McNaughton, 1986):

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$$\Omega = \left[1 + \left(\frac{\gamma}{\gamma + s}\right)\frac{rs}{ra}\right]^{-1} \tag{4}$$

where *ra* is the canopy aerodynamic resistance, *rs* is the stomatal resistance to vapour diffusion, γ is the psychrometric constant and *s* is the tangent of the vapour saturation curve.

Conceptually, the extreme values for the decoupling factor were as follows: $\Omega \to 1$ as $rs/ra \to 0$, implying that the net radiation is the only contributor to the evapotranspiration process and that vegetation is completely decoupled from atmospheric conditions; and $\Omega \to 0$ as $rs/ra \to \infty$, indicating complete coupling of vegetation with atmospheric vapour pressure deficit (VPD) and wind speed (Marin and Angelocci, 2011).

Results

Weather conditions

At EA1 (cultivar CTC 12), the average air temperature was 21.8 °C, ranging from 16.1 to 29.0 °C, with 1456 mm total rainfall. At EA2 (cultivar RB867515), the average air temperature was 22.7 °C, ranging from 16.8 to 30.3 °C and with 1318 mm total rainfall. The predominant wind direction was SE in both areas, with 51% of the values between 90 and 180°. These data were important for the fetch used in both experiments.

Crop energy balance and evapotranspiration

At EA1, the crop evapotranspiration (*ETc*) was higher than the reference evapotranspiration (*ETo*) during days with low *ETo*, and the opposite trend was detected during days with high *ETo*. EA1 had a mean *ETc* of 3.68 mm d^{-1} and mean *ETo* of 4.18 mm d^{-1}. At EA2, *ETc* was similar to *ETo* for all days, with a mean *ETc* of 2.92 mm d^{-1} and mean *ETo* of 2.89 mm d^{-1} at the maximum crop growth period. Overall, the average crop coefficient (*Kc*) for the full vegetative growth stage was 0.99 ± 0.29 (Figure 1a).

The *ETc* and *ETo* values resulted in a variable *Kc*, and this variability occurred because *Kc* was high when *ETo* was low and *Kc* decreased when *ETo* increased (Figure 1b, Table 1). Thus, there is an inverse relationship between *Kc* and VPD. When VPD was close to 0, *Kc* values were close to 1.7, and when VPD was around 4.0 kPa, the mean *Kc* was 0.9, showing that *ETc* had a smaller increase under high VPD conditions.

Sap flow and transpiration

The thermal conductivity of radial heat meter (*Kr*) was similar in both experimental areas. At EA1, *Kr* varied from 0.050 to 0.098 W C^{-1}, and this variation was caused by differences in stem diameter from 28 to 31 mm. At EA2, the *Kr* pattern was similar in all gauges and ranged between 0.035 and 0.045 W C^{-1}. These values were lower than those reported by Marin *et al.* (2008) for coffee with *Kr* reaching 0.180 W C^{-1}. These authors, however, also reported (in addition to long-term *Kr* variation) an influence of the size of sensors used in the study, that is, larger sensors have higher *Kr*. In the present study, we used gauges with 25 mm diameter at both experimental sites.

The four *SF* sensors installed at EA1 showed similar rates of water loss over the days, ranging from 0.23 to 0.50 L per stem for the 44^{th} and 49^{th} days of the year, respectively (Figure 2), representing 2.16 and 4.71 mm d^{-1} of transpiration. These values were higher than those detected at EA2, where water loss rates varied from 0.06 to 0.41 L per stem for the 177 and 140 days of the year (DOY), respectively, resulting in transpiration rates of 0.50 and 3.62 mm d^{-1}. This difference was because of differences in the environment energy availability: measurements in EA1 and EA2

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Table 1. Relationship between reference evapotranspiration ranges (*ETo*), crop evapotranspiration (*ETc*), crop coefficient (*Kc*) and basal crop coefficient (*Kcb*) from both experimental areas with RB867515 (2013) and CTC 12 (2011) cultivars

ETo (mm d^{-1})	*ETc* (mm d^{-1})	*Kc*	*Kcb*
0–2.0	1.6 ± 0.61	1.1 ± 0.31	1.1 ± 0.31
2.1–4.0	3.0 ± 0.89	1.0 ± 0.27	1.0 ± 0.25
>4.0	4.4 ± 0.99	0.8 ± 0.22	0.8 ± 0.13

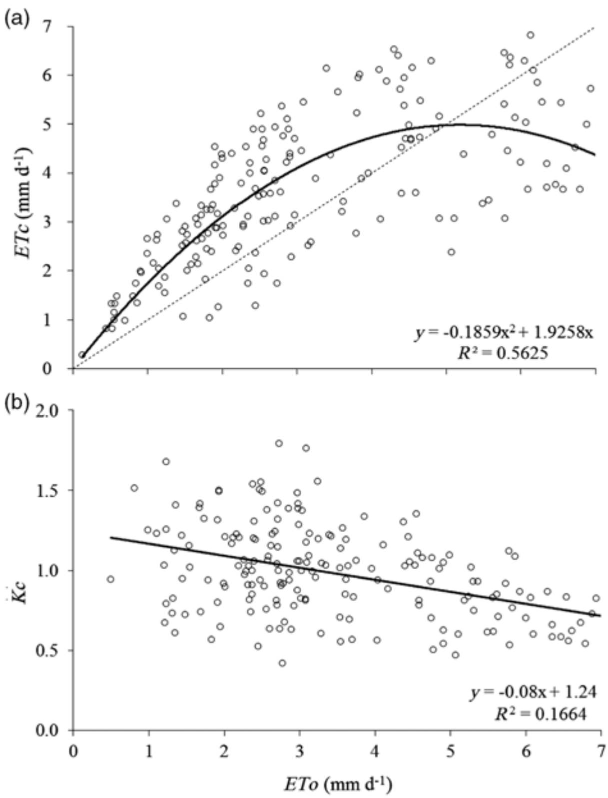

Figure 1. Relationship between reference evapotranspiration (*ETo*) and crop evapotranspiration (*ETc*) (a) and crop coefficient (*Kc*) (b) based on the BREB method for both experimental areas (dotted line is 1:1) (*p*-value <0.05 for both figures).

were taken in February 2012 (higher air temperature) and between May and June 2013 (lower air temperature), respectively.

At EA1, there were higher rates of water loss for the 48th and 49th DOY: *SF* = 4.14 and 4.71 mm d^{-1}, and *Qg* = 29.9 and 28.4 MJ m^{-2} d^{-1}, respectively. Low water loss rates were found on 43 and 44 DOY: *SF* = 2.64 and 2.16 mm d^{-1}, and *Qg* = 17.7 and 14.9 MJ m^{-2} d^{-1}, respectively. For EA2 (Figure 2b), water loss was relatively higher on 136, 140, 170 and 180 DOY (*Qg* varying between 13.0 and 16.7 MJ m^{-2} d^{-1} and *SF* between 3.46 and 3.62 mm d^{-1}) than on 147, 149 and 177 DOY (*Qg* between 2.4 and 3.3 MJ m^{-2} d^{-1} and *SF* between 0.49 and 0.64 mm d^{-1}).

Assuming that the daily-integrated *SF* was equivalent of crop transpiration (*T*), crop *T* values were higher than *ETo* values on most of the EA1 season (Figure 2a), except for few cases between 45 and 47 DOY, which will be discussed later. Comparing *T* (2.46 ± 1.04 mm) and *ETo* (2.39 ± 1.19 mm), we found that *T* was 3% higher than *ETo* (Figure 3a). The *SF* measurement campaigns were done mostly during low *ETo* periods (<3 mm d^{-1}). We also observed a trend for a reduction in the basal crop coefficient (*Kcb*) when *ETo* increased (Figure 3a), resulting in 95% of water loss from transpiration and 5% from soil water evaporation at both experimental sites.

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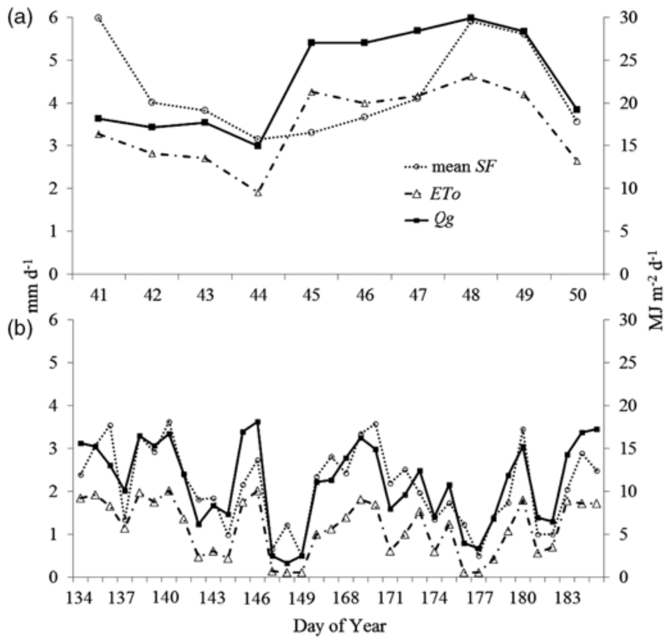

Figure 2. Temporal variation of mean sap flow (*SF*, mm d^{-1}), reference evapotranspiration (*ETo*, mm d^{-1}) and global radiation (*Qg*, MJ m^{-2} d^{-1}) for the analysed days on sugarcane crop in EA1 (a) and *EA2* (b).

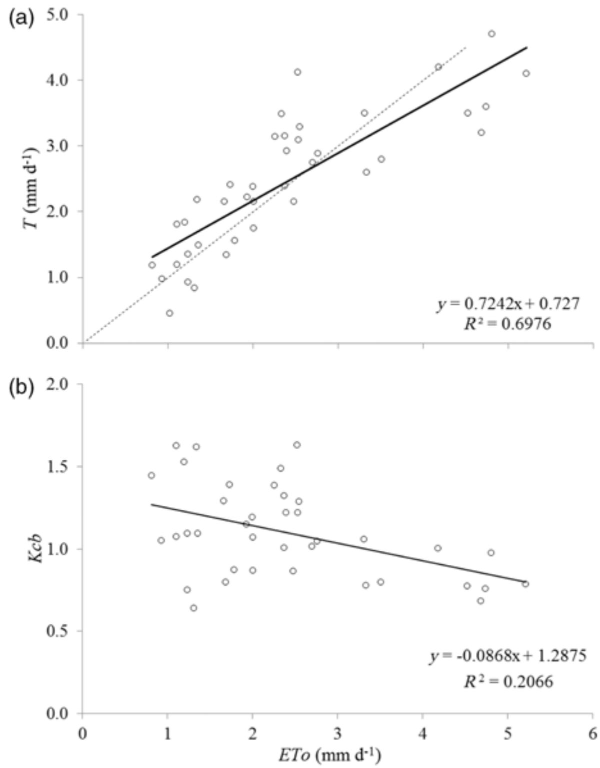

Figure 3. Relationship between sap flow transpiration (*T*) and reference evapotranspiration (*ETo*) (a) and basal crop coefficient (*Kcb*) (b) and *ETo* for both experimental fields (*p*-value <0.05 for both figures).

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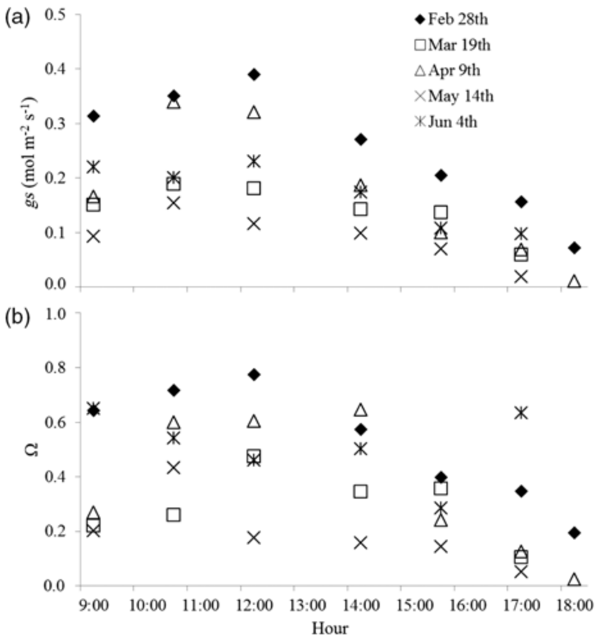

Figure 4. Daily variation of stomatal conductance (*gs*) (a) and decoupling factor (Ω) (b) for 28 February, 19 March, 9 April, 14 May and 4 June 2013 for EA2.

Stomatal conductance and decoupling factor

A rapid increase in *gs* was observed in days with high incident radiation (28 February and 19 April). The peak of *gs* (0.39 mol m^{-2} s^{-1}) occurred by noon, and there was a softer and constant decline in the afternoon, reaching values close to 0 (Figure 4a). This was also noticed on cloudy days with low insolation (19 March, 14 May and 4 June). However, *gs* had a small variation, and for some of the days the maximum *gs* values were considerably low (close to 0.20 mol m^{-2} s^{-1}).

On 28 February and 4 June 2013 (at EA2), the sugarcane canopy was decoupled from the atmosphere ($\Omega = 0.65$) in the morning (9:00 am) and showed increasing plant–atmosphere coupling ($\Omega = 0.1$) until sunset. On 9 April and 14 May, the sugarcane crop was coupled at 9:00 am ($\Omega = 0.2$), with such coupling decreasing at noon ($\Omega = 0.5$) and increasing towards sunset ($\Omega = 0.1$) due to high wind speed. On 14 May, for example, the sugarcane crop was coupled all-day-long ($0.1 < \Omega < 0.45$) due to high wind speed throughout the day (Figure 4b). The mean Ω values were between 0.19 (14 May 2013) and 0.52 (28 February 2013), showing that the sugarcane crop canopy was coupled to atmosphere.

Under low wind speed, the sugarcane crop tended to decouple from the atmosphere, resulting in water loss related mainly to the incident radiation. We found smaller Ω ($R^2 = 0.62$) under high wind speed (u) conditions (Figure 5a). Increases in *gs* also affected the relationship between the canopy and aerodynamic components, with high *gs* causing further decoupling ($R^2 = 0.7$) (Figure 5b). VPD probably had short interference on crop–atmosphere coupling when assessed individually, as shown in Figure 5c ($R^2 = 0.05$).

Discussion

During both crop cycles, when the BREB method was used, it was observed that the mean sensible heat flux (H) was 10% of the available energy (Rn-G) and that the mean latent heat flux was 85% of Rn-G. This high difference between H and LE was due to high water availability in the environment, resulting in a lower H flux on the sugarcane crop. In maize, Zeggaf *et al.* (2008) have detected a crop H flux of about 8% (and always <10% of available energy), and the remaining

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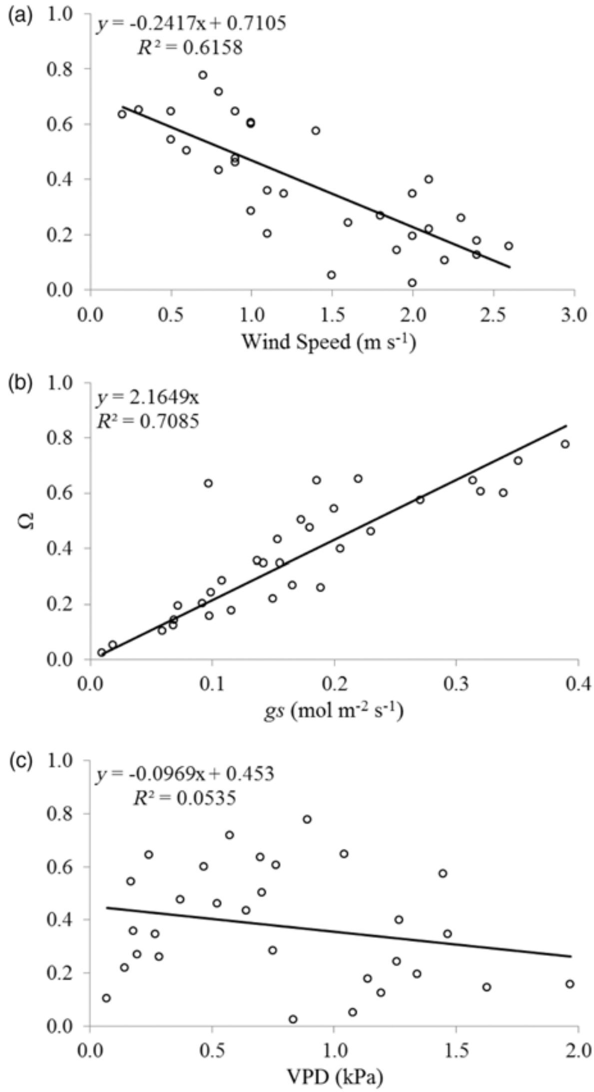

Figure 5. Relationship between decoupling factor (Ω), wind speed (a), stomatal conductance (b) and VPD (c) for EA2 (p-value <0.05 for all figures).

energy was used to *LE* flux. For a full irrigated coffee plantation, Righi (2004) has reported *LE* representing 64% and 80% of *Rn* and a mean *H* value about 29%. For the sugarcane crop, Cabral *et al.* (2012) have measured *LE* and *H* fluxes on an irrigated field in northern Brazil using the Eddy correlation method and reported values of 97% for the sum of *H* and *LE*.

According to the FAO 56 bulletin (Allen *et al.*, 1998), the *Kc* value for the maximum growth period of sugarcane is 1.25. However, here we estimated a lower mean *Kc* (0.99) compared with the FAO 56 bulletin, and this varied on daily basis, depending on *ETo* (Table 1). Our findings differ from those of Inman-Bamber and McGlinchey (2003) for irrigated sugarcane crop in Australia and Swaziland (for maximum growth period) and of Olivier and Singels (2012) for South Africa. Nevertheless, these authors did not mention the Ω values for experimental fields. For a Brazilian cultivar (RB92579), Silva *et al.* (2012) have reported an average *ETc* of 4.7 mm d^{-1} for a semi-arid area in northern Brazil, also using the BREB method and resulting in a constant *Kc* of 1.1. This crop response could be due to the same condition observed under higher *ETo*, when the atmospheric demand was high. According to Marin *et al.* (2005), differences in microclimatic

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conditions, especially atmospheric demand, are important for *Kc* determination, with *Kc* varying as function of VPD in a coffee plantation. The same relation was reported by Marin and Angelocci (2011) in a citrus orchard, where the crop had low water loss by transpiration under conditions of high atmospheric demand. Marin *et al.* (2016) have found that *Kc* decreases when *ETo* increases as a consequence of high plant–atmosphere coupling and high crop inner resistance, which limits the amount of water that plants can supply to the atmosphere. Even for sugarcane plantation (after full soil cover), *Kc* decreased with increasing *ETo*, highlighting that this trend might not be exclusive of tall sparse crops and for plants well coupled to the atmosphere.

Transpiration values were lower than observed by Chabot *et al.* (2005) in Morocco (Mediterranean semi-arid climate) where sugarcane grown in lysimeters had an average transpiration rate of 8.0 mm d^{-1}. However, *SF* measurements can result in an overestimation of the crop transpiration rate by up to 35%. Boehringer *et al.* (2013) have used the same method with resistors introduced into stems and reported up to 140 g per stem water loss and that *SF* might underestimate water loss by up to 5% when compared with gravimetric measurements.

There was a decreasing trend in the *T/ETo* ratio when *ETo* was higher than 3 mm d^{-1} (Figure 3a), resulting in a constant decrease in *Kcb* values (Figure 3b). A similar result was reported by Marin and Angelocci (2011) for acid lime trees, where transpiration did not follow *ETo* but stabilized when *ETo* reached 4 mm d^{-1}. This relationship between water loss and net radiation was also described by Marin *et al.* (2008) for a coffee plantation. Sakuratani and Abe (1985) have found that low radiation leads to a partial stomatal closure in sugarcane plants, and they also detected a decrease in transpiration due to decreasing direct radiation incidence from noon to sunset and consequent increase in diffuse radiation.

Although without practical applications, the time course of *Kcb* follows the *Kc* pattern (Table 1), providing an estimative of the soil component on sugarcane crop evapotranspiration. Because the measurements of *Kcb* and *Kc* were performed with two independent methods, it can be concluded that measurement errors were an issue.

Under water-deficit stress conditions, sugarcane has *gs* values between 0.15 and 0.25 mol m^{-2} s^{-1} (Machado *et al.*, 2009). Under irrigated conditions, sugarcane crops have higher *gs* values, decreasing in the afternoon due to increased VPD (Roberts *et al.* 1990). Recently, Eksteen *et al.* (2014) have reported average *gs* values of up to 0.10 mol m^{-2} s^{-1} for two sugarcane cultivars in South Africa, but this was not measured throughout the entire day. As described by Angelocci *et al.* (2004), *gs* patterns are usually influenced by many environmental factors, imposing a challenge to isolate the individual relationships between *gs* and VPD, leaf temperature and incident radiation. Also, no clear relationships were identified in this research between those environmental variables and *gs*.

Here, we found that *gs* affected the decoupling factor (mean $\Omega = 0.37$), and this finding disagrees with Silva *et al.* (2012), who found higher Ω (0.74) under irrigation than under low water availability (0.6) in a furrow irrigation sugarcane crop in northern Brazil. Eksteen *et al.* (2014) have reported decoupled sugarcane canopy (mean $\Omega = 0.81$) in South Africa for the N19 and G73 cultivars, and these results suggest that radiation is the main factor controlling evapotranspiration in warm and dry regions, such as northeast Brazil and South Africa, whereas wind speed and VPD are the main factors in cold and rainy regions.

According to Jarvis and McNaughton (1986), the effects of *gs* variation in leaf transpiration can only be extrapolated to another scale if environmental conditions around this leaf and target scale are similar for Ω and VPD. Considering the known *gs* spatiotemporal variability (Eiksteen *et al.*, 2014; Inman-Bamber and Smith, 2005; McNaughton and Jarvis, 1991; Nassif *et al.*, 2014; Smith *et al.*, 2005) and Ω variability, extrapolation should be done with caution from leaf to plant and for different crop species. Jarvis and McNaughton (1986) have also noted that, as a result of individual stomatal control, leaves of the same plant might have different transpiration rates and different plants in same environmental conditions might have different water use rates. This can explain the variation of sugarcane crop *Kc* (Table 1) with lower Ω (highly coupled canopy), and therefore, the

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crop would control water vapour exchange with the atmosphere. In contrast, incident radiation is mainly responsible for water loss when the crop canopy trends to be decoupled (high Ω) (Steduto and Hsiao, 1998).

Conclusions

The RB867515 and CTC12 sugarcane cultivars were coupled to the atmosphere in southeast Brazilian climatic conditions ($\Omega = 0.37$), with *Kc* and *Kcb* showing temporal variability due to reference evapotranspiration. These results indicate a strong relationship between sugarcane water loss and environmental variables, with a growth stage-specific *Kc* that often diverges from the FAO 56 bulletin recommendation. We found that almost all of the water loss was due to crop transpiration for both sugarcane cultivars, which has important implications for the irrigation management of this crop.

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