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# Crop coefficient changes with reference evapotranspiration for highly canopy-atmosphere coupled crops

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ABSTRACT

Despite of the great advancement of technologies for water supply, irrigation management remains inadequate in most areas. The lack of basic information on crop water needs is one of the causes for inadequate water use and irrigation management. The approach normally used to quantify the consumptive use of water by irrigated crops is the crop coefficient-reference evapotranspiration (Kc ETo) procedure. In this procedure, reference evapotranspiration (ETo) is computed for a grass or alfalfa reference crop and is then multiplied by an empirical crop coefficient (Kc) to produce an estimate of crop evapotranspiration (ETc). The ETo represents the non-stressed ET based on weather data. We selected three experiments with different crops in terms of physiology and planting arrangements to discuss the crop coefficient paradigm and its relation with reference evapotranspiration for highly canopy-atmosphere coupled crops. We found the Kc decreasing as ETo increased as a consequence of high plant atmosphere coupling and high crop inner resistance, which limits the amount of water the plant could supply to the atmosphere. Even for sugarcane plantation (after it completely covered the ground) Kc decreased with ETo, highlighting that trend might not be exclusive of tall sparse crops and for well coupled to the atmosphere. For these reasons, we suggested the definition of Kcb (for sparse crops) and Kc should take into account ETo ranges besides the components currently considered.

## 1. Introduction

Good irrigation practices lead to higher yields and incomes for producers but usually increases water use. Despite the advancement of technologies for water supply, irrigation management remains inadequate in most areas. The lack of basic information on crop water needs is one of the causes for inefficient water use and irrigation management.

To quantify the consumptive use of water by irrigated crops the crop coefficient-reference evapotranspiration (Kc ETo) procedure is often used. This approach makes it possible to consider the independent contributions of soil water evaporation and crop transpiration by dividing Kc into two separate coefficients as follows: Ke, a soil water evaporation coefficient; and Kcb, a crop transpiration coefficient (referred to as the basal crop transpiration coefficient) (Pereira et al., 2015). In this procedure, reference evapotranspiration (ETo) is computed for a reference crop and is then multiplied by an empirical crop coefficient (Kc) to produce an estimate of crop evapotranspiration (ETc).

This approach has been universally adopted as a procedure for scheduling and quantifying the water amount to be applied in the field and it has been supported by data along years, but the same data frequently shows the need of systematic improvement (Rosa et al., 2012; Taylor et al., 2015).

In this paper, we used data from different crops (citrus orchard, coffee and sugarcane plantations) in terms of physiology and planting arrangements to discuss the crop coefficient paradigm, and to show how this approach might be improved if the transpiration coupling to the atmosphere were considered. To do so, we utilized our previous studies showing canopy-atmosphere decoupling influencing the crop transpiration responses to weather under high evaporative demand (Marin et al., 2005; Marin and Angelocci, 2011; Nassif et al., 2014), which could be explained by the decoupling factor (Ω) approach proposed by McNaughton and Jarvis (1983).

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## 2. Materials and methods

### 2.1. Experiment 1: citrus orchard

The experiment was conducted in an orchard at the experimental area of the “Luiz de Queiroz” College of Agriculture (ESALQ) at University of São Paulo (USP), Piracicaba, São Paulo State, Brazil (latitude 22°42′S; longitude 47°30′W; 546 m amsl) from January 1998 to August 2000, with details described by Marin et al. (2005). The study was carried out during two seasons including the wet, hot summer and the dry, cold winter. The experimental field had 0.6 ha of 7-year-old plants of *Citrus latifolia* Tanaka grafted on stock *Citrus limonia* Osbeck growing in an orchard with the largest dimension oriented predominantly northwest to southeast. The spacing at planting was 7 m between plants and 8 m between rows. The average crown dimensions were 4.5 m (height) by 4 m (width). The soil was classified as Typic Rhodustults.

The diurnal course of leaf diffusive resistance ($r_s$) was determined at least once a month in 1998 using a steady state pre-calibrated porometer (LI 1600; Li-Cor, Inc.). The $r_s$ was measured on exposed and shaded leaves in the upper, middle and bottom canopy layers sampling 20 leaves 7 times each day from 0900 h to 1600 h (local time) (Angelocci et al., 2004).

The mean values of $r_s$ were used to compute the decoupling factor ($\Omega$) for a hipostomatous leaf, which was defined by the following equation as described by McNaughton and Jarvis (1983):

$$\Omega = \frac{1}{1 + \left[\frac{2r_s}{\left(\frac{s}{\gamma}+2\right)r_a}\right]} \tag{1}$$

where $r_s$ is the stomatal resistance to vapor diffusion measured by porometry; and $r_a$ is the bulk aerodynamic resistance of acid lime orchards calculated as previously described by Landsberg and Jones (1981) with p values ranging from 6.3–7.9.

Conceptually, the extreme values of $\Omega$ mean are: a) $\Omega \to 1$ as $r_s/r_a \to 0$ implying that the net radiation is the only contributor to the evapotranspiration process and that vegetation is completely decoupled from the atmospheric conditions; b) $\Omega \to 0$ as $r_s/r_a \to \infty$ indicating complete coupling of vegetation with atmospheric vapor pressure deficit and wind speed.

The overall crop evapotranspiration (ETc) was determined by the aerodynamic method (Thom et al., 1975) during the summer and winter of 1999 (Eqs. (2–6)). To measure the vapor concentration, aspirated copper-constantan thermocouple psychrometers (Marin et al., 2001) were used, mounted at 2.5 m, 3.5 m, 4.5 m and 6.5 m above the ground in a row between two trees. The wind speed was measured with Met-One anemometers (model OA14; 0.45 m s$^{-1}$ starting speed) at the same heights with an extra sensor at 8.5 m above the ground. Combinations of measurement heights for the vertical gradients were previously tested, and 2.5 m and 6.5 m were used as the most adequate levels of measurement (Pereira et al., 2002).

The dry period was preceded by 110 d without rain, and the orchard was irrigated with micro-sprinklers wetting the area under the crowns, which were scheduled to ensure 80% moisture as minimal soil content. In the same orchard, Machado and Coelho (2000) showed that the roots reach 1.5 m deep and that the bulk of the root was in the top 0.4 m of the soil. The frequency of irrigation was scheduled based on an agrometeorological water balance to avoid an insufficient water supply to match the atmospheric demand. The threshold for starting irrigation was placed at 80% of the field capacity which implied to irrigate twice a week during most part of the irrigation period.The daily ETc was calculated, and the data was averaged over 15 min, recorded at 10 s intervals and stored by a datalogger (CR7; Campbell Scientific, Inc.). The following equation was used to calculate the ETc:

$$\mathrm{ETc} = -\rho k^2 \frac{0,622}{P}(\bar{z}-d)^2 \times \left(\frac{\Delta u \Delta e}{\Delta z^2}\right) \mathrm{fe} \tag{2}$$

where $\rho$ is the air density (1.26 kg m$^{-3}$); $\lambda$ is the water latent heat (2.45 10$^6$ J kg$^{-1}$); $k$ is the von Karman constant (0.4); $P$ is the local atmospheric pressure (kPa); $z$ is the average between two measurement heights ($\Delta z$; $m$); $d$ is the zero plane displacement height (m), which is assumed to be 2/3 of crop height (approximately 4.5 m) following the reports by Stanhill and Kalma (1972) and Kalma and Fuchs (1976); $\Delta u$ is the wind speed difference between the two heights (m s$^{-1}$); $\Delta$e is the difference of water vapor pressure at the same two heights (kPa); and fe is an empirical correction function to take into account the atmospheric stability described by Thom et al. (1975). The following equations describe the fe function:

$$\mathrm{fe} = (1 - 16\mathrm{Ri})^{0.75} \quad \mathrm{Ri} < -0.01(\mathrm{unstable}) \tag{3}$$

$$\mathrm{fe} = (1 + 16\mathrm{Ri})^{-2} \quad \mathrm{Ri} > 0.01\,(\mathrm{stable}) \tag{4}$$

$$fe = 1 \tag{5}$$

$$\mathrm{Ri} = \frac{g\left(\frac{\Delta\theta}{\Delta z}\right)}{T\left(\frac{\Delta u}{\Delta z}\right)^2} \tag{6}$$

where Ri is the gradient Richardson number; $g$ is the gravitational acceleration (9.8 m s$^{-2}$); and $\Delta\theta$ is the vertical difference of potential temperature ($K$) set equal to $\Delta T$ as suggested by Rosenberg et al. (1983) due to the small $\Delta z$ used.

In 1999, the measurements started during the summer season (wet period) with high regional soil moisture and full interrow ground cover by small grass vegetation. The dry period was characterized by the decrease of regional soil moisture and by interrow grass drying, making citrus leaves and wet soil bulbs the main water vapor sources in the area.

Weather data collected from an automatic standard weather station (CR10X; Campbell Scientific, Inc.), located over grass 2 km from the experimental field, and were used to compute daily values of reference evapotranspiration (ETo) based on the Penman-Monteith equation as parameterized by Allen et al. (1998). Another identical weather station was installed inside the orchard, measuring the same variables during the experimental period.

In parallel with the micrometeorological measurements, trunk sap flow was measured in two trees with different crown sizes. These measurements were taken to observe the effect of the size of the leaf area on tree transpiration using the stem heat balance technique (Sakuratani, 1981; Baker and Van Bavel, 1987). Due to the large size of the trunk (greater than 0.2 m) and irregularity of its shape (resulting in poor contact with the sensor), it was necessary to install one sensor in each of the three main branches. The respective values were summed to determine the whole tree sap flow. We built each sensor, and each sensor was fed by a DC power supply, which dissipated between 1 W and 3 W depending on the branch diameter. The change in heat storage of the branch segment was also measured (Marin, 2000). All signals were monitored every 10 s by a CR7 datalogger (Campbell Inc.), which gave mean values every 15 min using the procedures described by Valancogne and Nasr (1989).

daily sap flow values for each branch were computed from the summation of the values at every time interval of measurement starting at sunrise when it was assumed that the tree had its maximal internal water capacitance and there was no significant change in the tree water storage in a period of 24 h. Therefore, the 24 h integrated values of sap flow were considered as representative of the daily transpiration of each plant. The transpiration rates were normalized by dividing them by the leaf area (LA) of the plant to obtain the transpiration rate on a LA unit basis (mm $m^{-2}$ of the leaf), measured with a LAI-2000Canopy Analyzer (Li-Cor, Inc.) in the two seasons and converted to LAI by dividing the LA by the canopy crown area projected on the ground.

### 2.2. *Experiment 2: coffee plantation*

The study was carried out in ESALQ-USP from August to October, 2002, as fully described in Marin et al. (2005). The experimental field had 0.25 ha of 5-year-old plants of *Coffea arabica* 'Mundo Novo' grafted on stock *Coffea canephora* 'Apoatã', growing in a hedgerow system, oriented predominantly northwest–southeast. Spacing at planting was 1 m between plants and 2.5 m between rows; during the experiment, average crown dimensions were 2.5 m height and 1.8 m width. The soil of the plot is classified as a Typic Rhodustults. The drip-irrigation was scheduled to ensure soil moisture exceeding 80 % of field capacity, assuming an effective root depth of 1.0 m, based on an agrometeorological water balance. Drip-irrigation lines were placed along the base of the stems in the plant rows

ETo was calculated as showed in Experiment 1. The overall crop evapotranspiration (ETc) was determined by the surface energy balance using the Bowen ratio (β) method, based on vertical differences of air temperature (ΔT) and vapor pressure (Δe) by measuring them 1.5 m and 3.5 m above the ground. The reliability of the method was tested by rules proposed by Perez et al. (1999). These two variables were measured with an aspirated copper-constantan thermocouple psychrometer (Marin et al., 2001) mounted 1.5 m and 3.5 m above the ground. The psychrometer heights were chosen following Pereira et al. (2002). Daily ETc was calculated with data averaged over 15 min, which were recorded at 10-second intervals and stored by a datalogger (CR7, Campbell Scientific, Inc., Logan, USA). (8)Equations (7) and were used to estimate ETc, as follow:

$$\beta = \gamma \frac{\Delta T}{\Delta e} = \frac{\Delta T}{\left(1+\frac{s}{\gamma}\right)\Delta \mathrm{Tu} - \Delta T} \quad (7)$$

$$\mathrm{ETc} = \frac{\mathrm{Rn} - G}{\lambda(1+\beta)} \quad (8)$$

where ΔTu is the wet-bulb temperature difference between 1.5 and 3.5 m, s is the slope of the saturation vapor pressure curve at the wet-bulb temperature, $\gamma$ is the psychrometric constant and λ is the latent heat of vaporization; Rn is the net radiation (REBS Inc., model Q7.1-L) and G is the soil heat flux (REBS Inc., model HFT3-L).

As the experiment was conducted during the dry period in Piracicaba/SP, following 90 days without rain, soil in the interrow was dry and initially without ground vegetation. As soon as the measurements started, the whole region was wetted by frequent rain, and a rise in air temperature promoted the growth of grass in the interrow of the crop. After 30 days, the interrow spaces were filled by vegetation. In order to evaluate the effect of soil moisture and ground vegetation on water consumption of the coffee plantation, the data were divided in two parts, the first period (dry) being between 22/08 and 21/09 and the second one (wet) between 22/09 and 30/10.

The stem heat balance method (Baker and Van Bavel, 1987) was used to estimate the transpiration rate of coffee plants. Commercially available stem sap flow gauges (three SGB50 and one SGB35, Dynamax, Inc., Houston, USA) were installed on the stem of four coffee plants near the micrometeorological tower. The operation of the sap flow gauges was controlled by the same datalogger used for micrometeorological measurements. The 24 h integrated values of sap flow were considered as representative of the daily transpiration of the each plant. Transpiration rates were normalized by dividing them by the plant's leaf area to obtain 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. The plants' leaf area was determined by two indirect methods and the average of leaf area obtained with the two methods was used in the calculations. The LAI of each plant was calculated by dividing LA by the canopy crown area projected on to the ground. Crown area was determined by measuring the mean diameter of trees in which sap flow data were taken and the mean orchard crown area of 10% of the trees in the orchard.

Diurnal courses of stomatal conductance (gs) were determined on five days over the experimental period with a steady state porometer (LI 1600, Li-Cor, Inc., Lincoln, USA) on exposed and shaded leaves in the upper, middle and bottom canopy layers, sampling 20 leaves seven times each day from 0900 to 1600 h (local time). The decoupling factor (Ω) was also calculate for a hypostomatous leaf being defined by Eq. (1), using the bulk aerodynamic resistance of coffee crop, calculated from relations presented by Barros et al. (1995).

### 2.3. *Experiment 3: sugarcane plantation*

This experiment was carried out in Piracicaba ESALQ-USP from October of 2012 to April of 2015. The experimental plot had 2.3 ha of plant cane cultivar RB867515 irrigated by a center-pivot. Irrigation management was based on an agrometeorological water balance to ensure soil moisture exceeding 80% of field capacity, assuming an effective root depth of 0.4 m. The planting spacing was 1.4 m between plants and nearly 15 buds per meter were used during planting.

The overall crop evapotranspiration (ETc) was determined by the surface energy balance using the Bowen ratio ($\beta$) method, as in the experiment 2 and fully described by Nassif et al. (2014) and following the Perez et al. (1999) recommendations for checking the measurements quality.

The plants' leaf area was determined using the gap-fraction method (LAI-2000. Li-Cor, Inc.). Diurnal courses of stomatal conductance (gs) were determined on five days over the experimental period with an infra-red gas analyzer (IRGA, ADC) on exposed leaves, sampling 10 leaves six or seven times each day from 0900 to 1800 h (local time), weather depending. The decoupling factor (Ω) was also calculate for a hypostomatous leaf is defined by Eq. (1).

## 3. Results

Along the citrus whole experiment (Experiment 1), ETo was systematically higher than ETc, with averages of ETo = 4.4 mm $d^{-1}$ and ETc = 2.8 mm $d^{-1}$ in the wet summer season (SS) and ETo = 2.8 mm $d^{-1}$ and ETc = 0.90 mm $d^{-1}$ in the winter season. During SS ETc followed ETo relatively closer than it was along the WS (Fig. 1), in which ETc was almost flat below 1 mm $d^{-1}$ despite ETo ranged from 1 to 4 mm $d^{-1}$.

During the SS, ETo ranged from 3 to 7 mm $d^{-1}$, but ETc did not exceed 4 mm $d^{-1}$ (Fig. 2a), but rather ETc tended to reach a ceiling value when ETo surpassed 4 mm $d^{-1}$. Average Kc values ranged from 0.6 to 0.17 for the whole experiment time (Fig. 2B) which were related with the slope of the linear equations of Fig. 2A. Fig. 2B shows the Kc downward trend as ETo increases for both seasons, which might be a consequence of stabilization of ETc in days with ETo high atmospheric. It is interesting to see that even during the WS, when the atmospheric demand is relatively lower than SS, the same trend was observed (Fig 2B). The relations between the ETc and ETo resulted in a mean Kc value during the summer of 0.65 ± 0.11 ranging from 0.51 to 0.94 (Fig. 1a). In the winter, the mean Kc value ranged from 0.10 to 0.52 with a mean value of 0.24 ± 0.12 (Fig. 2b). The summer Kc value compared well with

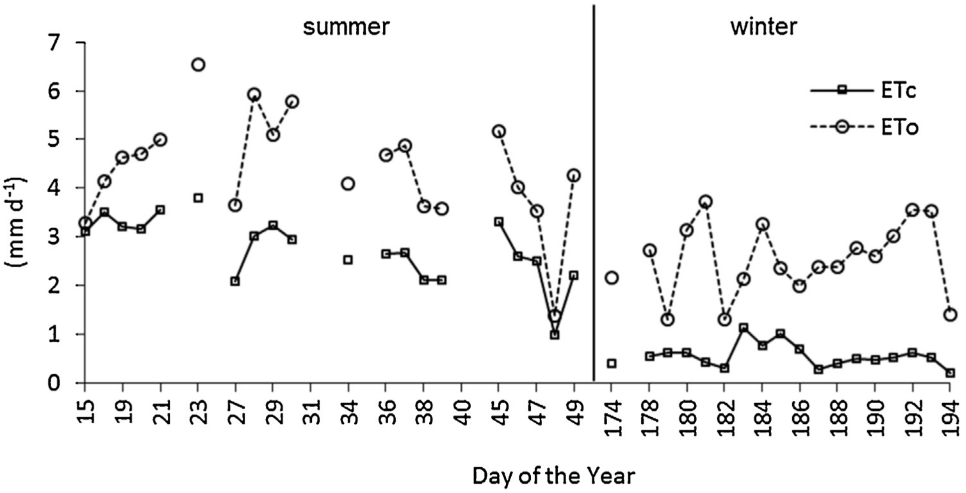

**Fig. 1.** Daily variation of acid lime orchard evapotranspiration (ETc) and reference evapotranspiration (ETo) in the Experiment 1.

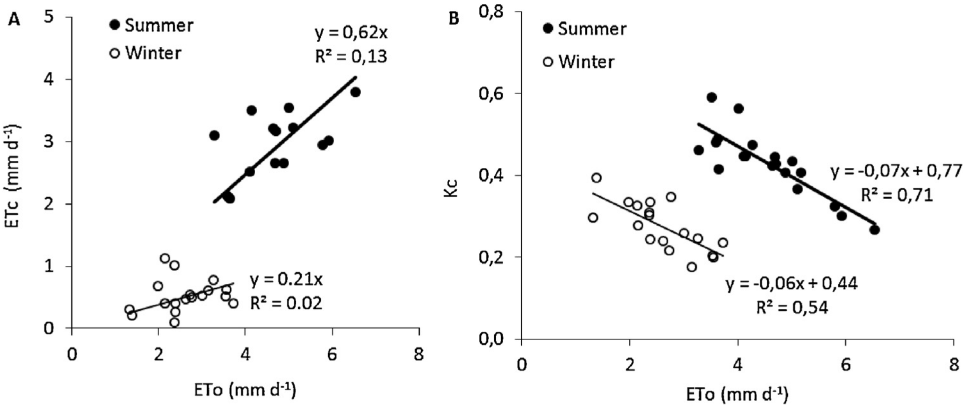

**Fig. 2.** Relationship between acid lime evapotranspiration (ETc, A) and crop coefficient (Kc, B) with the reference evapotranspiration (ETo) in two seasons.

other Kc values reported for humid climates (Rogers et al., 1983; Boman 1994; Doorenbos and Pruitt, 1977; Castel et al., 1987; Allen et al., 1998; Morgan et al., 2005), but the winter Kc values were nearly half of the Kc values reported by Allen et al. (1998) for non-ground covered orchards.

Winter Kc values for citrus were lower than those observed by Alves et al. (2007) under the same climate and soil conditions, with average values of 0.70 and 0.26 for the summer and winter, respectively. These Kc values, however, were within a similar range reported by others (Doorenbos and Pruitt, 1977; Rogers et al., 1983; Castel et al., 1987; Boman,1994; Allen et al., 1998; Morgan et al., 2005; Carr, 2012). The Kcb value was 0.41 ± 0.08 for the wet period and 0.28 ± 0.07 for the dry period, and these Kcb values were comparable to previously reported values (Boman, 1994; Allen et al., 1998; Alves et al., 2007).

Coffee measurement in Experiment 2 showed similar values of ETc in relation to ETo, with average ETc = 3.1 mm d$^{-1}$ and average ETo = 3.2 mm d$^{-1}$ (Fig. 3) At the time of year when measurements occurred, coffee plants were usually recovering their physiologic activity and preparing for the coming flowering phase, which is usually induced after a certain period of cold and dry weather. During the time when those measurements were taken, weather was already warmer and the crop had a higher physiological activity, which could explain the close relation between ETc and ETo observed in that experiment.

The mean value of Kc obtained was 0.99, ranging from 0.6 to 1.9 (Fig. 4b). The value of Kc is essentially composed of two terms: the basal coefficient (Kcb), which represents the plant transpiration, and the evaporative coefficient (Kce), which represents the bare soil water evaporation (Allen et al., 1998). Although Kce was originally defined for bare soil, in orchards it can be defined in terms of the interrow water loss, including weed transpiration. The average value of Kce obtained was 0.24. In Hawaii, Gutiérrez and Meinzer (1994) found an mean Kc value of 0.66 for *Coffea arabica*, var. Catuaí, with LAI ranging from 1.4 to 7.5. Blore (1966) in Kenya found a range of values less than 0.86, while at the same experimental site found Kc to be equal to 0.69.

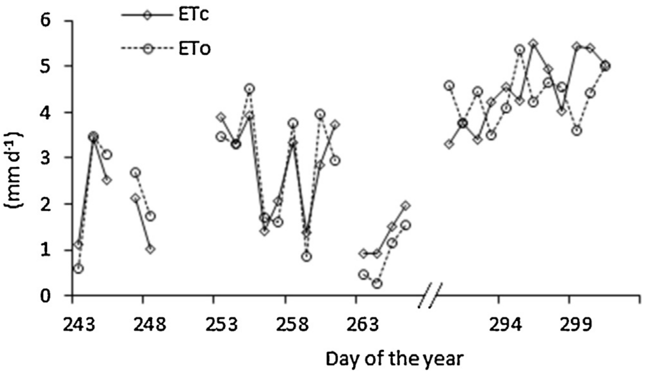

**Fig. 3.** Daily variation of overall coffee evapotranspiration (ETc), and reference evapotranspiration (ETo) in the Experiment 2.

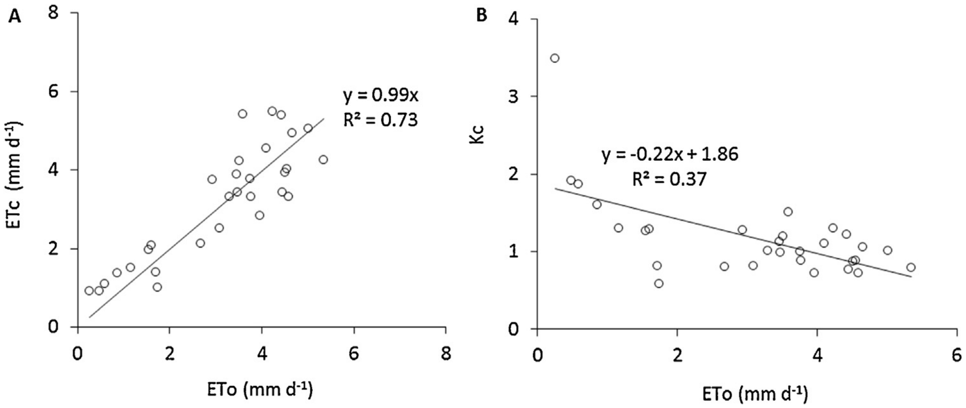

**Fig. 4.** Relationship between coffee evapotranspiration (ETc) and reference (ETo) evapotranspiration (A), and relationship between crop coefficient (Kc) and ETo (B).

Although Kc and Kcb obtained in this study are within of a range proposed by Allen et al. (1998), they were, respectively, 44% and 23% higher than those found by Gutiérrez and Meinzer (1994). One of the causes for low values of Kc observed at Hawaii seems to be the differences in the micrometeorological conditions compared with the Brazilian plantation, especially with respect to atmospheric water demand. This reason was also advanced by Gutiérrez and Meinzer (1994) to explain the variation in Kc between two years with different values of ETo, since the mean value of ETo observed in Hawaii was 5.9 mm d$^{-1}$ and in Brazil ETo was around 3.2 mm d$^{-1}$.

The relation between ETc and ETo for coffee plantation whose ratio, given by the slope of the straight line forced to pass by the origin (Fig. 4a), represents the Kc values, indicates mean value of Kc around 1 and with a downward trend for Kc values as ETo increased (Fig. 4b).

Sugarcane ETc was usually higher than the ETo along of the three years of measurements, with average ETc = 3.43 mm d$^{-1}$ and average ETo = 4.05 mm d$^{-1}$. (Fig. 5). Considering the planting and harvest dates of such sugarcane plantation, it is possible to see the ETc trend following both crop development and weather conditions (i.e. raising during the winter-spring (second semester) and decreasing along the summer-autumn (first semester) seasons. 2014 was one of the driest and hottest years of the climatic registers in the region and the very high ETc data observed might be related to this, with maximum values reaching 7.9 mm d$^{-1}$ (Fig. 5). On average, ETc was nearly 16% higher the ETo (Fig. 6a), and Kc showed a decreasing trend from 1.4 (for values of ETo less than 2 mm d$^{-1}$) to 1.0 for ETo higher than 6 mm d$^{-1}$. In the sugarcane field, the mean Kc for the whole experiment was 1.21, ranging from 0.5 to 2.52. The Kc for plant cane (first year of Experiment 3) was 1.04; and for the first ratoon (second year of experiment 3) it reach 1.31 in average, while in the second ratoon season it decreased again to 1.23 (Figs. 5 and 6). The year average might be biased by the period of the year was taken, as it varied from year to year. Anyway these data reasonably agreed with FAO suggested values for sugarcane (Allen et al., 1998). Fig. 6b shows Kc decreasing with ETo, as a consequence of the highly coupled plant-atmosphere conditions, as already observed by Nassif et al. (2014) but this relationship seems to be less marked than ones observed for citrus (Fig. 2b) and coffee (Fig. 4b).

## 4. Discussion

Although a shallow root system might be conditioned by frequent irrigation, leading to an insufficient water supply to match the atmospheric demand, this probably was not the case in the experiments since the irrigation was managed to meet the crop water requirements. Also, for coffee (Experiment 2) a 1.0 m soil profile was excavated close to a coffee plant and roots were found exploiting all the profile, with the bulk of the roots in the top 0.9 m. For sugarcane, soil water measurements showed the irrigation was sufficient to assure high crop evapotranspiration rates as well as the roots were using water from a deep soil layer.

As mentioned before, for the three crops, we saw evidence that Kc decreases under high ETo values (mainly due to the decrease in transpiration) (Fig. 3a) even under high soil water content. Furthermore, papers concerning the relationship between leaf diffusive conductance and environmental variables have demonstrated that citrus (Hall et al., 1975; Kahiri and Hall, 1976; Cohen and Cohen 1983; Syverstsen and Lloyd, 1994; Angelocci et al., 2004), coffee (Butler, 1977; Barros et al., 1995; Fanjul et al., 1985) and sugarcane (Machado et al., 2009, Gonçalves et al., 2010; Roberts et al., 1990; Nassif 2014) leaves restrict the water loss under high atmospheric water demand mainly through stomatal closure. Indeed, such stomatal response to air temperature and vapor pressure deficits (VPD) with stomatal closure in response to an increase of these weather variables. Therefore, the relationship between the ETc and ETo for the three crops (Figs. 2, 4, and 6b) seems to be due to an increase of inner resistances to water transport of plants when subjected to conditions of high atmospheric water demand due to an opposite tendency of transpiration and stomatal movement in relation to increased air vapor pressure deficit (McNaughton and Jarvis, 1983).

Results from Angelocci et al. (2004), Marin et al. (2005) and Nassif et al. (2014) showed the response of leaf conductance (gs) to air temperature, VPD and solar radiation (SRad) having a quadratic relationship in which gs decreases when the atmosphere demands high evapotranspiration rates. Based on values of VPD, SRAD and air temperature, it was possible to observe gs increasing with weather conditions equivalent to ETo less than 4.5 mm d$^{-1}$ for the three crops (Angelocci et al., 2004; Marin et al., 2005; Nassif et al., 2014) and decreasing thereafter for higher ETo values. Despite the high variability of gs, these relations corroborates the hypothesis that trees control the transpiration as the ETo increases, supporting the proposition for the use of different Kcb values for discrete ETo ranges. Based on this, Table 1 shows proposed values for Kc and Kcb in different ETo ranges for the three crops. For all of them, Kc (or Kcb) values decreased as the ETo increased, which may represent an interesting way to improve the water management in orchards under localized irrigation (for coffee and citrus for instance) and an important way to save water for extensive irrigated sugarcane plantations. Comparing the Kc values for ETo < 2 and ETo > 4 mm d$^{-1}$, it decreased by 40%, 13% and 25% for coffee, sugarcane and acid lime, respectively (Table 1).

Low values of $\Omega$ indicates the influence of wind speed and VPD on ETc and T, i.e., the crop transpiration becomes conditioned by

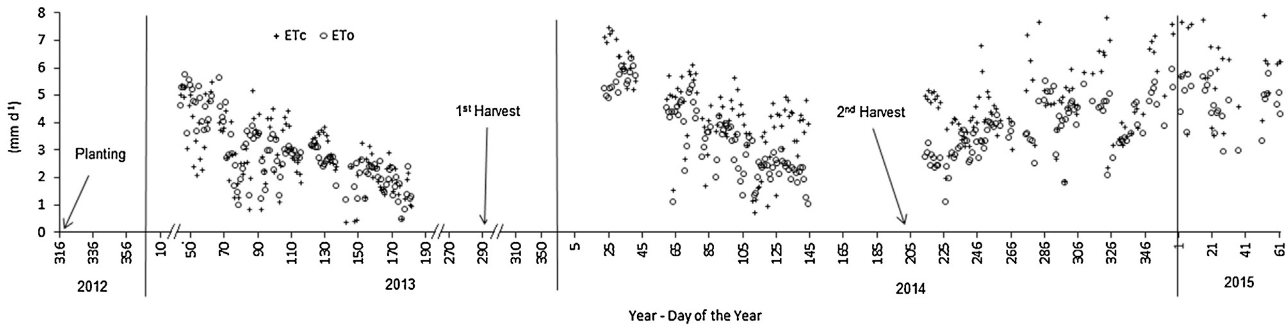

**Fig. 5.** Daily variation of reference evapotranspiration (ETo-mm) and overall sugarcane evapotranspiration (ETc, mm) in the Experiment 3.

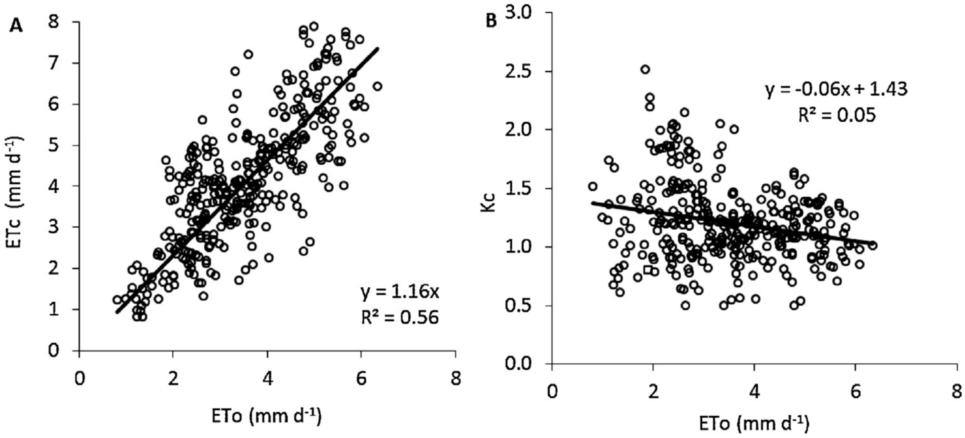

**Fig. 6.** (A) Relationship between sugarcane evapotranspiration (ETc) and reference (ETo) evapotranspiration, and (B) relationship between crop coefficient (Kc) and ETo.

**Table 1**
Values of Kc (and/or Kcb) for three ranges of ETo for citrus orchards, coffee and sugarcane plantations, under the experimental conditions. The standard deviation is found in the brackets.

| | Coffee | | Sugarcane | Acid lime (summer) | | Acid lime (winter) | |
|---|---|---|---|---|---|---|---|
| ETo range | Kc | Kcb | Kc | Kc | Kcb | Kc | Kcb |
| <2 mm d-1 | 1.57 [0.84] | 1.27 [0.48] | 1.26 [0.46] | 0.74 [0.14] | 0.53 [0.11] | 0.39 [0.16] | 0.46 [0.09] |
| 2–4 mm d-1 | 1.03 [0.23] | 0.87 [0.18] | 1.15 [0.27] | 0.71 [0.12] | 0.45 [0.03] | 0.31 [0.15] | 0.35 [0.06] |
| >4 mm d-1 | 0.94 [0.20] | 0.67 [0.08] | 1.10 [0.20] | 0.68 [0.10] | 0.37 [0.06] | 0.22 [0.05] | 0.24 [0.03] |

**Table 2**
Average values of decoupling factor for coffee, citrus and sugarcane plantations.

| Crop | Decoupling factor |
|---|---|
| Coffee | 0.09 |
| Citrus | 0.11 |
| Sugarcane | 0.22 |

aerodynamic conditions rather than radiation conditions, which imposed a tendency of larger crop evapotranspiration rates. As Jarvis (1985) postulated, $\Omega$ tends to be gradually lesser in tall rough crops (mainly with discontinuous ground cover) due to a reduction of aerodynamic resistances of the canopy caused by a vigorous air mixing and a high crop roughness. Therefore, in conditions of high available energy, wind speed and VPD, which are normally found when ETo surpasses 4.0 mm d$^{-1}$, it may be expected that tall horticultural species with high inner resistances to water flow do not respond directly to the atmospheric water demand. This might explain the different results for Kc for coffee interesting to note that for even such a less rough canopy crop as sugarcane, $\Omega$ was low as 0.22, suggesting that there was sufficient air mixing and canopy roughness for coupling the canopy to the atmosphere (Table 2).

Figs. 2, 4 and 6a show a linear relationship between ETc and ETo, indicating that the decrease in the transpiration rate under high atmospheric demands was almost compensated by a direct response interrow evapotranspiration rate (i.e., soil evaporation plus grass transpiration) during the summer, mainly for coffee and acid lime. This compensation was based on the fact that the rate of transpiration by short vegetation and soil water evaporation are normally decoupled from the atmospheric conditions because Rn is the major contributor to the evapotranspiration process (McNaughton and Jarvis, 1983). In turn, this compensation was an effect of acid lime trees on interrow vegetation and soil reducing the wind speed near the ground.

Allen et al. (1998) claimed that the Kc values must be used under standard climatic conditions, as sub-humid climate, minimum relative humidity of 45% and wind speeds averaging 2 m s$^{-1}$ and that variations in wind speed may alter aerodynamic resistance and, hence, the crop coefficients mainly for tall crops. They also inferred that under high wind speeds and low relative humidity, Kc tends to increase.

However, some aspects observed in those three experiments were slight different from the aspects postulated by Allen et al. (1998). Firstly, we noted that Kc for coffee and citrus had a small variation as the ETo remained up to 5.5 mm d$^{-1}$, which is mainly due to the role of interrow vegetation. Secondly, high wind speed and low air relative humidity affected crop evapotranspiration and decreased Kcb values as ETo increased.

The small number of crops analyzed in this study and the absence of sufficient climatic diversity suggest further studies are needed on crop evapotranspiration responses to weather under highly canopy-atmosphere coupled crops. Nevertheless, we observed that T and ETc did not linearly follow ETo for these two crops in all variation ranges, which results in a decrease in Kc (and Kcb) values as ETo increased. Furthermore, Kc values observed for the sugarcane plantation (after it completely covered the ground) decreased with ETo, highlighting that trend might not be exclusive of tall sparse crops (and for well coupled to the atmosphere) such coffee and citrus. For these reasons, we complement the conclusions of Marin et al. (2005) and Marin and Angelocci (2011) suggesting the definition of Kcb (for sparse crops) and Kc even for tropical crops such as sugarcane might be based on other components beyond those suggested by Allen et al. (1998), i.e. crop development stage and presence or absence of weeds, to be applied for practical purposes.

## 5. Conclusions

For these crops, leaves reduced the stomatal conductance under high air temperature, vapor pressure deficit and solar radiation, even with high soil water availability. Strong canopy coupling to the atmosphere – due to relatively low aerodynamic resistance and moderate-to-high leaf resistance – enhanced this response pattern in the coffee, citrus and sugarcane under these conditions. These characteristics caused the Kc and Kcb to inversely vary as a function of ETo. Based on these results, it was proposed that the Kc and Kcb recommendation for practical purposes should include their variation also in function of ETo.

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