Expl Agric. (2005), volume 41, pp. 187–197 © *2005 Cambridge University Press*
doi:10.1017/S0014479704002480 *Printed in the United Kingdom*

EVAPOTRANSPIRATION AND IRRIGATION REQUIREMENTS OF A COFFEE PLANTATION IN SOUTHERN BRAZIL

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(*Accepted 27 September 2004*)

SUMMARY

Crop evapotranspiration (ETc) was measured as evaporative heat flux from a drip-irrigated coffee (*Coffea arabica*) plantation with 5-year-old trees using the Bowen ratio-energy balance technique. Crop transpiration (T) was determined with the stem heat balance method. Irrigation requirements were determined by comparing the ETc and T with reference evapotranspiration (ETo) derived from the Penman-Monteith equation and expressed as the ETc/ETo (Kc) and T/ETo (Kcb) ratios. Also, relationships were established between ETc and T and class A pan evaporation (ECA). The influence of inter-row vegetation on ETc was analysed, since the measurements were taken in a period of transition between dry-wet seasons. The average Kc value obtained was 1.00. The strong coupling of coffee plants to atmospheric conditions and high sensitivity of coffee plants to large vapour pressure deficits and air/leaf temperatures caused variations in Kcb in relation to ETo. Kcb ranged from 0.67, when ETo exceeded 4 mm d^{-1}, to 1.27 when ETo was less than 2 mm d^{-1}. When vegetation did not occupy the inter-row ground spaces, T represented about 0.87ETc, but 0.68ETc when ground vegetation filled the inter-row spaces.

INTRODUCTION

Coffee plants have been cultivated in Brazil since 1727 and are of great importance to the economy of the country. There are more than 2.4 million ha of commercial coffee, and in the last 15 years, the crop has expanded to regions where droughts occur frequently, often coinciding with fruit expansion. These conditions mean that irrigation is almost essential in such regions (Camargo, 1985). Currently, it is estimated that about 200 000 ha of coffee are being grown under irrigation in Brazil.

In spite of great advances in technology for water supply and the economic importance of coffee, irrigation management is inadequate in most Brazilian coffee regions: the large amount of water applied normally exceeds the crop's requirements, with wastage of water, energy and nutrients (Camargo, 2002). Regarding this, Carr (2001) concluded in his exhaustive review of the water relations in coffee that estimates of water for irrigation are still imprecise and subject to large errors depending on local circumstances and the system of irrigation used.

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The first studies on water needs of coffee plantations were performed in Kenya, using hydrological models and *in situ* soil water balances (Pereira, 1957; Wallis, 1963; Blore, 1966). In Hawaii, studies with the same objectives were carried out by Gutiérrez and Meinzer (1994a, b). These represented an important advance in methods and techniques for analysis and experimentation on the water consumption of coffee plantations. In Brazil, experiments on the water requirements of coffee are recent (Santinato *et al*., 1996; Arruda *et al*., 2000; Villa Nova *et al*., 2003). However, because of the territorial extent of Brazil, its great climatic variability, the diversity of coffee production systems and irrigation methods, knowledge of the water needs of coffee is insufficient to quantify the water requirements of the crop and to assure correct irrigation management.

In contrast to annual crops, with low height and full soil cover, orchards and hedgerow crops have discontinuous soil cover and taller plants. Because of these differences, investigations of the water needs of orchards or hedgerow crops, such as coffee, demand different experimental and data analysis procedures, and adjustment to the micrometeorological, biometrics and ecophysiological specificity of tall sparse crops.

The objectives of this study were to assess the water used by a drip-irrigated coffee plantation in southern Brazil using different measurement techniques in order to determine the two components of Kc: the basal coefficient (Kcb), which represents the plant transpiration, and the evaporative coefficient (Kce), which represents the bare soil evaporation (Allen *et al*., 1998). The role of inter-row vegetation in the water consumption of a coffee crop was also studied. The study also evaluated the micrometeorological factors affecting transpiration, crop and reference evapotranspiration relationships and the implications for estimating actual rates of water use and irrigation management.

MATERIAL AND METHODS

The study was carried out in a coffee plantation in the experimental area of the Agricultural College 'Luiz de Queiroz', University of São Paulo, Piracicaba, State of São Paulo, Brazil (lat. 22°42′S; long. 47°30′W; 546 m asl) from August to October 2002. 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 area is classified as a Typic Rhodustults. The irrigation was scheduled to ensure soil moisture exceeding 80 % of field capacity, assuming an effective root depth of 1.0 m. Drip-irrigation lines were placed along the base of the stems in the plant rows. To the east, south and west sides of the coffee plantation (southeastern is the predominant direction of the wind at Piracicaba), there was another coffee plantation approximately 1.0 m in height, cultivated under drip irrigation. To the north side, there were pastures with *Brachiaria* averaging 0.8 m in height.

A 4-m instrument tower was positioned in the middle of the field and the upwind fetch was about 20 times the crop height, acceptable when the Bowen ratio is small (Heilman *et al*., 1989). Net radiation (Rn) was measured with a net radiometer (NR Lite, Kipp & Zonen, Inc., Delft, The Netherlands) mounted 4 m above the soil surface. Soil heat flux (G) at the surface was measured using three heat flux plates (HTF3, REBS, Seattle, WA, USA) placed 30 mm below the soil surface, with two beneath the plant canopy and another in the inter-row space.

The overall crop evapotranspiration (ETc) was determined by the surface energy balance using the Bowen ratio (β) method, based on measurements of vertical differences of air temperature (ΔT) and humidity (Δe). These 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 positions were chosen following Pereira *et al*. (2003). Daily ETc was calculated with data recorded at 10-second intervals and averaged over 15 minutes, and stored by a datalogger (CR7, Campbell Scientific, Inc., Logan, VT, USA). Equations (1) and (2) were used to estimate ETc, as follow:

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

$$ETc = \frac{Rn - G}{\lambda(1 + \beta)} \tag{2}$$

where: ΔTu is the wet-bulb temperature difference between 1.5 and 3.5 m, s is the slope of the saturation vapour pressure curve at the wet-bulb temperature, γ is the psychrometric constant and λ is the latent heat of vaporization; Rn is the net radiation and G is the soil heat flux.

Meteorological data from an automatic standard weather station (CR10X, Campbell Scientific, Inc.) located 200 m from the experimental field were used to compute daily values of reference evapotranspiration (ETo), based on the Penman-Monteith equation as parameterized by FAO-56 Bulletin (Allen *et al*., 1998). A Class A pan installed in the same place supplied the daily evaporation data to establish relations with coffee transpiration and evapotranspiration.

As the experiment was conducted during the dry period in Piracicaba/SP, following 90 days without rain, soil in the inter-row 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 inter-rows of the crop. After 30 days, the inter-row 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 being between 22/08 and 21/09 and the second one 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, TX, USA) were installed on the stems 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 each plant. Transpiration

Table 1. Leaf area (LA) determined by indirect methods: canopy analyser (LAI2000) and by counting and measuring leaves, and mean leaf area index calculated on the basis of the projected canopy crown area.

	LA (m^2)			
Method	Plant 1	Plant 2	Plant 3	Plant 4
LAI2000	9.1	13.8	11.6	6.1
Counting	9.6	14.0	11.1	5.9
Mean	9.3	13.9	11.4	6.0
LAI	3.6	4.5	3.8	2.4

rates were normalized by dividing them by the plant's leaf area to obtain transpiration rate on a unit leaf area 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. In the first, the leaves of four plants were counted and a sample of 10 % of the leaves of each plant was used to determine the mean area of the leaves (*MLA*):

$$MLA = LW\ 0.703 \tag{3}$$

where: L is the largest length, W the largest width of leaves. The constant 0.703 is the slope of the straight line of a linear regression between individual leaf areas measured with an area meter (LI3100 Area Meter, Li-Cor Inc., Lincoln, NE, USA) and the product of LW of 50 leaves randomly sampled from the coffee plants studied ($r^2 = 0.99$).

Leaf area was also determined with a LAI-2000 Canopy Analyzer (Li-Cor, Inc). The average leaf area obtained with the two methods was used in the calculations. Table 1 presents the leaf area (LA) and leaf area index (LAI) for the four coffee plants studied. The LAI of each plant was calculated by dividing LA by the canopy crown area projected on to the ground.

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.) on exposed and shaded leaves in the upper, middle and bottom canopy layers, sampling 20 leaves seven times each day from 09.00 to 16.00 hours (local time).

The decoupling factor (Ω) for a hypostomatous leaf is defined by equation (4) following McNaughton and Jarvis (1983) and Jarvis (1985a). Conceptually, the extreme values for the decoupling factor are: a) $\Omega \rightarrow 1$ as $r_s/r_a \rightarrow 0$, implying that the radiation is the only contributor to the evapotranspiration process, and vegetation is completely decoupled from the atmospheric conditions; b) $\Omega \rightarrow 0$ as $r_s/r_a \rightarrow \infty$, indicating a complete coupling of vegetation with the atmospheric vapour pressure deficit (VPD) and wind speed. The decoupling factor for Hawaii was calculated for two periods while for Brazil it was determined over five days.

$$\Omega = \frac{1}{1 + \left[\frac{2r_s}{(s/\gamma + 2)r_a}\right]} \tag{4}$$

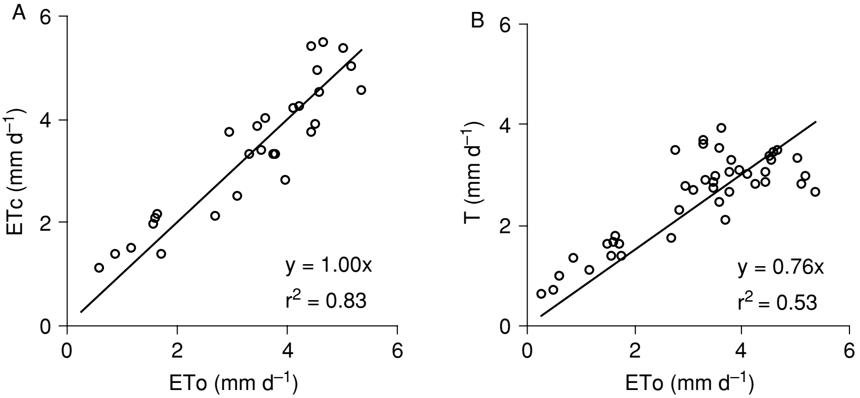

Figure 1. Relationships between crop (ETc) and reference crop (ETo) evapotranspiration (A), and between crop transpiration (T) and ETo (B).

where r_s is the stomatal resistance to vapour diffusion, measured by porometry; r_a is the bulk aerodynamic resistance of a coffee crop, calculated from relations presented by Barros *et al*. (1995).

RESULTS

As shown in Figure 1A, the ratio between ETc and ETo represents the Kc values and is given by the slope of the straight line forced to pass through the origin. The mean value of Kc obtained was 1.0 (ranging from 0.6 to 1.9). The value of Kc is essentially composed of two terms, i.e. basal (Kcb) and evaporative (Kce). Figure 1B shows the straight line for the relation between T and ETo, which resulted in a Kcb value of 0.78. These values are close to those suggested by Allen *et al*. (1998), but Carr (2001) emphasized that the values remain to be validated. Although Kce was originally defined for bare soil, in orchards it can be defined in terms of the inter-row water loss, including weed transpiration. The average value of Kce was 0.24.

Water requirements can be estimated from Class A pan evaporation (ECA). Figure 2A shows the relationship between ETc and ECA, which yields an average ETc/ECA ratio of about 0.61, and 0.45 for T/ECA (Figure 2B), with ECA ranging from 1 to 10 mm day^{-1}. The T/ECA value is useful for practical purposes when using methods for 'under tree' systems of irrigation (micro-sprinkle or drip irrigation). The straight line did not fit the data of Figures 1B and 2B well, since transpiration tended to stabilize when ETo and ECA values exceeded 4.0 and 6.0 mm day^{-1} respectively.

Evaporation from inter-row spaces can be computed by the difference between T and ETc. In the first 30 days, inter-row evapotranspiration (ETg) represented only 13 % of overall evaporation (Figure 3A) while in the subsequent period ETg increased to represent 32 % of crop evaporation (Figure 3B). Figure 4 shows the daily variation of ETc and T throughout the experiment, illustrating the increase in ETc because of the development of inter-row vegetation in contrast to T stabilization.

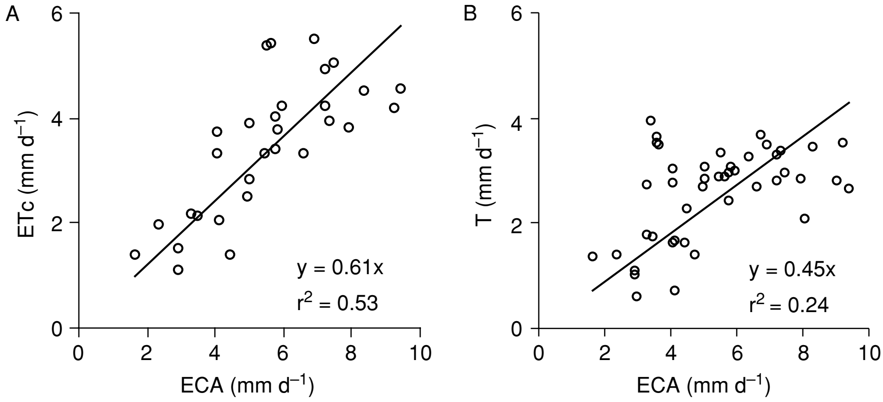

Figure 2. Relationship between crop evapotranspiration (ETc) and class A pan evaporation (ECA) (A) and between coffee transpiration (T) and ECA (B).

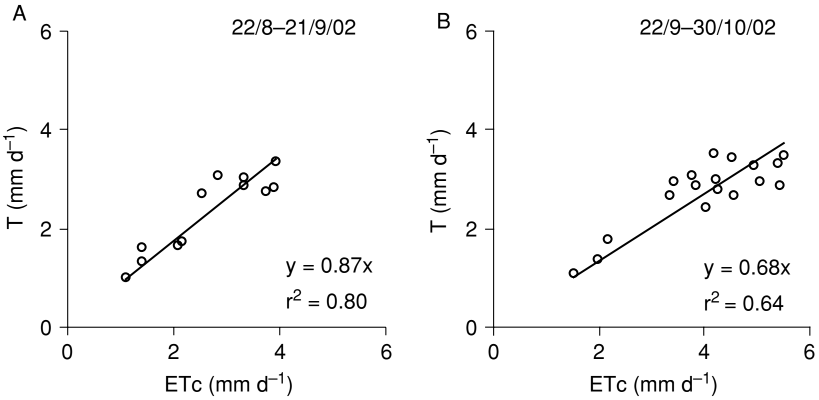

Figure 3. Relationship between coffee transpiration (T) and crop evapotranspiration (ETc) in two successive periods: (A) without active vegetation at the inter-row; (B) inter-row covered by active grass vegetation.

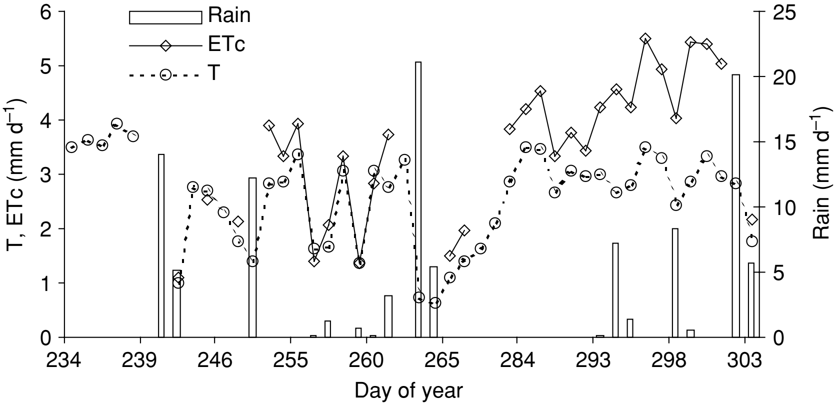

Figure 4. Daily variation of coffee transpiration (T), evapotranspiration (ETc), and measured rainfall (Rain) throughout the experimental period.

DISCUSSION

In Hawaii, Gutiérrez and Meinzer (1994b) found a 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 below 0.86, while Wallis (1963) at the same experimental site found Kc to be equal to 0.69. Although Kc and Kcb obtained in this study are within the range proposed by Allen *et al*. (1998), they were, respectively, 44 % and 23 % higher than those found by Gutiérrez and Meinzer (1994b). Variety, root-stock, plant age and management system may be factors responsible for differences in Kc and Kcb, but the main cause for the low values of Kc observed at Hawaii seems to be the differences in the micrometeorological conditions compared with Brazil, especially with respect to atmospheric water demand. This reason was also advanced by Gutiérrez and Meinzer (1994b) to explain the variation in Kc between two years with different values of ETo, since the mean ETo rate observed in Hawaii was 5.9 mm d^{-1} and in Brazil it was around 3.2 mm d^{-1}.

All coffee species are evergreen and the natural habitat of *C. arabica* is the understorey of the rainforest in the high plains of Ethiopia; it is therefore not adapted to high water demand conditions (Willson, 1985). Several workers have investigated the relationships between leaf conductance and environmental variables. Coffee leaves restrict the water loss under high atmospheric demand: for example, Butler (1977) and Barros *et al*. (1995) established a large dependence of stomatal conductance on air temperature and VPD, with stomatal closure occurring in response to an increase in these variables; Fanjul *et al*. (1985) verified that coffee plants show a reduction in stomatal conductance with an increase in photosynthetic photon flux density.

Although a shallow root system might be conditioned by frequent irrigation (Bull, 1963), leading to an insufficient water supply to match the atmospheric demand, this probably was not the case in this study because a 1.0 m soil profile was excavated close to a coffee plant and roots were found exploiting the whole profile, with the bulk of the roots in the top 0.9 m. This corroborates the assumption that an increase of stomatal resistance explains the reduction in the transpiration rates above an ETo boundary value.

In Figure 1B, a non-linear relationship between T and ETo was observed confirming this assumption. The non-linearity between these variables may be explained by the high inner resistance to water transport of coffee plants when subjected to conditions of high atmospheric water demand, as demonstrated for other horticultural species (Syvertsen and Lloyd, 1994; Tardieu and Simonneau, 1998), due to opposing trends of transpiration and stomatal movement in relation to increasing air VPD (McNaughton and Jarvis, 1983).

To diagnose the causes of the non-linear relationship observed in Figure 1B, the decoupling factor (Ω) was calculated with data obtained in Brazil and Hawaii (Gutiérrez and Meinzer, 1994b) (Table 2). The low Ω observed in the two localities demonstrates the influence of wind speed and VPD on the determination of ETc and T in both coffee plantations, i.e. crop transpiration was conditioned by aerodynamic rather than radiation conditions (Jarvis, 1985a). As McNaughton and Jarvis (1983) and

Table 2. Decoupling factor values (Ω) for coffee plantations in Brazil and Hawaii.

Data from Brazil		Data from Hawaii[†]		
DOY[‡]	Ω	LAI	Period	Ω
254	0.14	1.4	1–8/11/91	0.23
267	0.04	7.5	25–31/08/92	0.10
289	0.11			
295	0.05			
297	0.10			
Mean	0.09			0.17

[†] Source: Gutiérrez and Meinzer (1994).
[‡] DOY = day of the year with porometric measurements.
LAI = leaf area index.

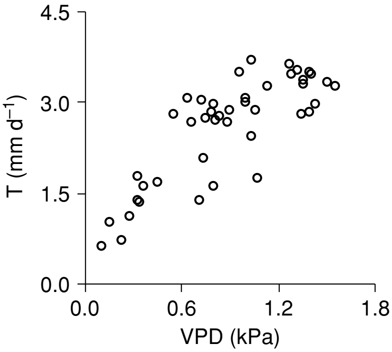

Figure 5. Relationship between daily transpiration (T) and mean vapour deficit pressure (VPD) measured at 1.5 m height in the coffee plantation.

Jarvis (1985b) postulated, in tall horticultural crops with discontinuous ground cover, Ω tends to decline gradually due to a reduction in the aerodynamic resistance of the canopy, caused by vigorous air mixing and a high crop roughness. Therefore, under conditions of high available energy, and high wind speed and VPD, normally found when ETo exceeds 4.0 mm day^{-1}, it could be expected that tall horticultural species with large inner resistance to water flow would not respond directly to the atmospheric water demand. This is the case for the coffee plantation analysed here, since the high atmospheric water demand caused stomatal closure and, as a consequence, a reduction in the ratio between T and ETo. Figure 5 shows the relationship between T and VPD, illustrating the influence exerted by aerodynamic conditions over coffee plants with transpiration rates restricted under high VPD values, especially in excess of about 1.2 kPa.

In Figure 1A, we note a linear relationship between ETc and ETo, which seems to indicate that the decline in transpiration rates under high atmospheric demand was compensated for by an increase in evapotranspiration rates from the inter-row (i.e. soil evaporation plus grass transpiration). This compensation is based on the

Table 3. Mean and standard deviation values of air temperature (Tair) and vapour pressure deficit (VPD) inside the coffee plantation and at the standard weather station in two successive periods of the experiment.

	Tair (°C)		VDP (kPa)	
Period	Coffee	Station	Coffee	Station
22/8–21/9/02	25.6, *s.d.* 3.7	24.2, *s.d.* 3.6	1.5, *s.d.* 0.6	1.3, *s.d.* 0.6
21/9–30/10/02	28.5, *s.d.* 5.2	27.3, *s.d.* 5.1	1.7, *s.d.* 0.8	1.9, *s.d.* 1.1

fact that the rate of transpiration by short vegetation is normally decoupled from atmospheric conditions and Rn is the major contributor to the evapotranspiration process (McNaughton and Jarvis, 1983; Jarvis, 1985b), mainly at low wind speeds and because of 'isolation' from overhead conditions caused by the wind-break effects of the coffee plants.

As the inter-row vegetation responds linearly to the available radiant energy, an increase in the inter-row space filled by ground vegetation results in a rise in evapotranspiration rates. The effect of inter-row ground cover (Figures 3 and 4) on the relationship between T and ETc resulted from changes in the energy balance, with a large amount of available energy converted to latent heat flux by ground vegetation. By comparing the variation in the air temperature (Tair) and VPD inside the coffee plantation with data from the standard weather station (Table 3), it is possible to observe that Tair increased throughout both periods of measurements with crop temperatures higher than those in the weather station at all times. VPD in the coffee plantation was higher than in the weather station in the first period but lower in the second one. This also demonstrates the influence of ground vegetation on the overall evapotranspiration process in a coffee plantation.

Allen *et al*. (1998) commented that the Kc values proposed must be used under standard climatic condition (sub-humid climate, minimum relative humidity of 45 % and wind speeds averaging $2\,\mathrm{m\,s^{-1}}$), and that variations in wind speed may alter aerodynamic resistances and hence crop coefficients, especially for tall crops. They also inferred that under high VPD and wind speed Kc would tend to increase. However, some conditions observed in the coffee plantation were different from those postulated by Allen *et al*. (1998).

Firstly, it was noted that the Kc value for coffee did not vary when ETo ranged from 0.5 to $5.4\,\mathrm{mm\,d^{-1}}$ because ground vegetation responded linearly to the available energy (Figure 1A); therefore, the use of a unique Kc for any range of ETo can be accepted. Secondly, high VPD and wind speed tends to restrict the coffee transpiration and change the ratio between T and ETo as ETo increases (Figure 1B). As a result, for tall horticultural crops with discontinuous ground cover and localized irrigation, it seems inadequate to adopt a unique value of Kcb. Alternatively, perhaps two or three values of Kcb could be used for different ranges of ETo (Table 4) to better assess the required irrigation.

For these reasons and for practical purposes, the definition of Kcb (and maybe of Kc for others crops) might be based on other components, beyond those suggested

Table 4. Mean and standard variation values for Kcb of coffee plantation for different ranges of ETo.

ETo range	Kcb	s.d.
$< 2\ \mathrm{mm\ d^{-1}}$	1.27	0.48
$2\text{–}4\ \mathrm{mm\ d^{-1}}$	0.87	0.18
$> 4\ \mathrm{mm\ d^{-1}}$	0.67	0.08

by Allen *et al*. (1998) (i.e. crop development stage, presence or absence of weeds). As proposed by Carr (2001), it confirmed that Kc and Kcb values suggested by Allen *et al*. (1998) must be validated considering agronomic, biometrics and ecophysiology aspects of crops, in order to improve the irrigation management.

Acknowledgements. The authors wish to thank The State of São Paulo Research Foundation (FAPESP) and The National Council for Scientific and Technological Development (CNPq) by the financial support of this research and the fellowships granted.

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